MINING CERTIFICATE SERIES

COLLIERY EXPLOSIONS AND RECOVERY WORK

SAFETY FIRST

WHITAKER

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PITMAN'S MINING CERTIFICATE SERIES
EDITED BY JOHN ROBERTS, D.I.C., M.I.MIN.E., F.G.S.

COLLIERY EXPLOSIONS AND RECOVERY WORK

MINING CERTIFICATE SERIES

BEING A SET OF TEXTBOOKS PREPARED FOR CANDIDATES FOR CERTIFICATES UNDER THE MINES DEPARTMENT.

EDITED BY

JOHN ROBERTS

D.I.C., M.I.MIN.E., F.G.S.

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Colliery Explosions and Recovery Work. By J. W. WHITAKER, B.Sc., F.I.C., M.I.MIN.E.

SIR ISAAC PITMAN & SONS, LTD., PARKER ST., KINGSWAY, W.C.2

COLLIERY EXPLOSIONS AND RECOVERY WORK

A TEXTBOOK FOR CANDIDATES FOR THE FIRST-CLASS MANAGERS' AND UNDER-MANAGERS' CERTIFICATES

BY

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EDITOR'S PREFACE

THE Mining Certificate Textbooks are being specially prepared to meet the requirements of candidates for certificates of competency as managers and under-managers of mines.

The subjects of the examinations are given in the following extracts from the syllabus issued by the Board for Mining Examinations—

FOR FIRST-CLASS CERTIFICATES—

1. WINNING AND WORKING. Systems of laying out and working, under varying circumstances, of coal and other stratified deposits included under the Coal Mines Act—The geology of these deposits—Methods of supporting roof and sides—Boring and sinking—Blasting and general knowledge of explosives.

2. THEORY AND PRACTICE OF VENTILATION. The properties, identification, and practical estimation of gases met with in mines—Sources and effects of heat in mines—Natural ventilation, fans, and other ventilators—The distribution and control of the air underground—Construction, use, and testing of safety lamps.

3. EXPLOSIONS IN MINES, UNDERGROUND FIRES AND INUNDATIONS, THEIR CAUSES AND PREVENTION. Coal dust—Spontaneous heating—Rescue operations, apparatus, and organization—Recovery of mines after explosions, fires, and inundations.

4. MACHINERY. Winding, hauling, pumping, mechanical coal-cutting and conveyors, etc.—Methods of transmission of power—Strength of materials.

5. SURVEYING, LEVELLING, AND DRAWING. Determination of magnetic declination—Loose and fast needle dialling—Calculation of areas and volumes—Contour lines and levelling—Traversing with the theodolite underground and on the surface—Connecting of surface and underground surveys—Triangulation—Mine plans and sections—The use, care, and testing of instruments.

N.B.—Each candidate must produce a plan of a mine survey and a section prepared from an underground levelling made and drawn by himself, with the original plottings, and the notes from which the plottings have been made, and the work must be certified by him as having been carried out by himself. The plan and section prepared from an underground levelling must have been made and drawn not more than twelve months before the date of the examination.

6. GENERAL MANAGEMENT AND MINING LEGISLATION. Organization and surface arrangements under varying circumstances—Mines Acts—General and special regulations and orders, and other legislation.

In addition to the written examination, there will be a *viva voce* examination.

For Second-class Certificates—

The questions set in the respective papers for Second-class Certificates will be of a nature suitable for practical working miners.

1. Systems of laying out and working, under varying circumstances, of coal and other stratified deposits included under the Coal Mines Act—Methods of supporting roofs and sides—Boring against old workings—Shot firing.

2. Ventilation, the properties, identification, and practical estimation of gases met with in mines—Natural ventilation, fans and other ventilators—The distribution and control of the air underground—Construction, use, and testing of safety lamps.

3. Explosions in mines, underground fires, and inundations, their causes and prevention—Coal dust—Spontaneous heating—Rescue operations, apparatus, and organization.

4. Machinery and plant in common use in a colliery, including the use of electricity, and with special reference to safety.

5. Arithmetic (simple rules)—Elementary surveying and levelling.

6. Mines Act—General and special regulations and orders—Writing of reports.

In addition to the written examination, there will be a *viva voce* examination.

The first set of textbooks in the series covers the scope of the examination for second-class certificates, but in the case of two of the subjects, namely, *Mining Law and Management* and *Explosions in Mines*, it has been considered advisable to embrace the scope of both the first- and the second-class examinations in one volume devoted to each subject.

Prior to the establishment of the Board for Mining Examinations under the Coal Mines Act, 1911, it would have been impracticable to have prepared suitable textbooks to deal separately with each subject, on account of the lack of uniformity that existed in the matter of standards of examination ruling in the various coalfields where the examinations were held. The establishment of one governing body to control and arrange examinations has resulted in standardization, and, incidentally, a general raising of the standard of qualifications.

Several years' experience under the existing system has enabled mining teachers and lecturers to form sound plans for the training of candidates, but however efficient a teacher may be, the student's progress depends on his application to

private study. It is hoped that the present series of text-books will be found of especial value to students preparing for examinations, and to mining students generally.

The following books will form the first series—

Mining Machinery, by T. Bryson, A.R.T.C., M.I.Min.E.
Arithmetic and Surveying, by R. M. Evans, B.Sc., F.G.S., M.I.Min.E.
Mine Ventilation and Lighting, by Chas. D. Mottram, B.Sc., M.I.Min.E.
Methods of Working, by Prof. Ira C. F. Statham, B.Eng., F.G.S., M.I.Min.E.
Mining Law and Mine Management, by Alexander Watson, A.R.S.M.
Colliery Explosions and Recovery Work, by J. W. Whitaker, B.Sc., F.I.C., M.I.Min.E.

The publishers have been fortunate in securing the services of authors who have had extensive experience in training and preparing students for mining examinations, and who have otherwise distinguished themselves by their contributions to mining literature. In this series of textbooks the subjects have been treated by the respective authors in a manner "suitable for practical working miners."

As the authors have aimed to meet the requirements of candidates for certificates, the keynote has necessarily been "Safety First," since in every mining operation safety precautions must be uppermost in the minds of officials and miners. The same policy governs the mining examinations.

The permission of the Controller of H.H. Stationery Office has been obtained to reproduce certain Examination Questions.

AUTHOR'S PREFACE

In the following chapters, only a small space has been devoted to the description of actual colliery explosions, as they are only of importance inasmuch as each explosion teaches a lesson, and these lessons are far better learned at the feet of science. Consequently, it has been the aim throughout the book to keep to the fore the *scientific* aspect of the problems connected with firedamp and coal-dust explosions, and spontaneous combustion and gob fires. The excellent work of the Safety in Mines Research Staff under the direction of Prof. R. V. Wheeler has been referred to several times, as will be seen in the text, and the results of the investigations of Dr. J. S. Haldane, Dr. L. Hill, and Prof. H. Briggs have been utilized in dealing with their respective problems.

However, lest certain sections of the work should as a consequence of the above treatment appear unimportant, especially as greater safety is now being obtained, an introductory chapter has been devoted to an extract from a report on the explosion at Felling Colliery in 1812.

This report should serve to impress on all the terrible nature of these calamities, which are essentially the same in their devastating effects nowadays as they were 50 or 100 years ago. Moreover, the deeper mines now being worked are certainly drier, "dustier," and more "gassy" than the mines worked in the last century; in other words, modern mines are *potentially* far more dangerous. If, then, explosions are to become still rarer, it will only be through unceasing vigilance on the part of all concerned, through knowledge and care on the part of those engaged in the mine, and through continuous and thorough research work by those who investigate the problems experimentally. It is needless to say that there are still many problems unsolved in this field, though the knowledge already gained is by no means small.

The fact should be emphasized that diminution in the

number and extent of mine accidents, whether arising from explosions, haulage, winding, falls of roof, or other common cause, is not an indication that the danger from the source in question is diminishing. Such danger is largely inseparable from practical mining operations. The diminution in the accident rate is merely an indication that the danger from the particular source is being more truly estimated, that the conditions for safety are becoming known, and that the necessary precautions are being taken in the mine.

J. W. WHITAKER

DEPT. OF MINING,
UNIVERSITY COLLEGE,
NOTTINGHAM,
1927.

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COLLIERY EXPLOSIONS AND RECOVERY WORK

CHAPTER I

INTRODUCTORY

DESCRIPTION OF EXPLOSIONS

Felling Colliery Explosion, 1812

The original report on this disaster was written by the Rev. J. Hodgson, the able author of the *History of Northumberland.* The extract here given, however, is taken from a summary of the Rev. J. Hodgson's report by John Holland in *The History and Description of Fossil Fuel, the Collieries, and Coal Trade of Great Britain,* a book full of interesting and useful information, though published as long ago as 1835—

In the forenoon of the 25th of May, 1812, the villages in the neighbourhood of Felling Colliery were alarmed by a tremendous explosion. The subterraneous fire broke forth with two heavy discharges from the John Pit, followed by one from the William Pit. A slight trembling, as from an earthquake, was felt for about half a mile round the workings; and the noise of the explosion, though dull, was heard to three or four miles distance, and much resembled an unsteady fire of infantry. Immense quantities of dust and small coal accompanied these blasts, and rose high into the air in the form of an inverted cone. The heaviest part of the ejected matter, such as corves, pieces of wood, and small coal, fell near the pit; but the dust, borne away by a strong west wind, fell in a continued shower from the pit to the distance of a mile and a half. In the village of Heworth, it caused a darkness like that of early twilight, and covered the roads so thickly that the footsteps of passengers were strongly imprinted in it. The heads of both the shaft-frames were blown off, their sides set on fire, and their pullies shattered in pieces—those of the John Pit downcast gin, being on a crane not within the

influence of the blast, were preserved. The coal dust, ejected from the William Pit (the upcast) into the drift or horizontal parts of the tube, was about three inches thick, and soon burnt to a light cinder. Pieces of burning coal, driven off the solid stratum of the mine, were also blown up this shaft.

As soon as the explosion was heard, the wives and children of the colliers ran to the working-pit. Wildness and terror were pictured in every countenance. The crowd from all sides soon collected, to the number of several hundreds, some crying out for a husband, others for a parent, or a son; and all deeply affected with an admixture of horror, anxiety, and grief. The machine being rendered useless by the irruption, the rope of the gin was sent down the pit with all expedition. In the absence of horses, a number of men, whom the wish to be instrumental in rescuing their neighbours from their perilous situation seemed to supply with strength proportionate to the urgency of the occasion, put their shoulders to the shafts of the gin, and wrought it with astonishing expedition. By twelve o'clock, thirty-two persons, all that survived this dreadful calamity, were brought to daylight, and along with them the dead bodies of two boys—three other boys dying in a few hours. Only twenty-nine persons were, therefore, left to relate what they observed of the appearances and effects of this subterraneous thundering: one hundred and twenty-one were in the mine when it happened, and eighty-seven remained in the workings. Eight persons had come up at different intervals, a short time before the explosion. It is impossible to describe the shrieks, howlings and wringing of hands which characterized the persons on the spot at this crisis: they who had their friends restored, hastened with them from the dismal scene, and seemed, as Mr. Hodgson remarks, for a while to suffer as much from excess of joy as they had lately done from grief.

The eighty-seven persons who remained in the mine, had all been employed in the workings to which the plane-board was the general avenue, and as none had escaped by that way, the most intense apprehension for their safety existed. At noon, nine courageous individuals descended the John Pit, in expectation of meeting with some of them alive. As the firedamp would have ignited at candles, they lighted their way by steel-mills, which gave light by turning a plain thin cylinder of steel against a piece of flint. Knowing that a great number of the workmen would be at the crane when the explosion happened, they attempted to reach it by the plane-board, but their progress was intercepted at the second pillar by the prevalence of choke-damp

—the sparks from the steel-mill falling into the noxious fluid like drops of blood. Being, therefore, deprived of light, and nearly poisoned for want of atmospheric air, they retraced their steps to the shaft, and then attempted to pass up the narrow boards: in these, they were stopped at the sixth pillar by a thick smoke, which stood like a wall the whole height of the board. With difficulty, they found their way to the pit bottom, persuaded that the mine was on fire, and before they had all ascended another explosion, though much less severe than the first, took place. The men at the bottom saved themselves by suddenly lying down on their faces—though they felt the heat and energy of the blast very seriously.

As these adventurous men were successively drawn to bank, all their reports as to the chance of any person remaining alive in the mine were equally hopeless; but the proposition to exclude the atmospheric air from the mine, in order to extinguish the fire, was received with cries of "Murder," and with determinations of opposing the proceeding. Many of the widows continued about the mouth of the John Pit during the whole of the night, with the hope of hearing the voice of a husband or a son calling for assistance.

After another ineffectual attempt to proceed from the shaft towards the workings, the hope was abandoned, and it was resolved to exclude the atmospheric air, in order to extinguish the fire which the explosion had kindled in the mine, and of which the smoke ascending the William Pit was a sure indication. This shaft was accordingly filled with clay about seven feet above the ingate, or entrance into the drift; and the John Pit mouth was covered over with loose planks. In two days afterwards, twenty fothers (tons) of additional clay were thrown into the William Pit, in order to insure its being air tight; in the next place, a scaffold, at 25½ fathoms from the surface, was suspended on side ropes, each six inches in circumference in the John Pit. Upon this a large quantity of straw, and afterwards twenty-six fothers of clay, were thrown, to render the whole air tight. On the 1st of June, this suspended mass fell into the pit, and also another, subsequently constructed; at length, a scaffolding of planks on stout beams of timber, was laid across . . .

Preparatory to re-opening the mine (a few weeks afterwards) a brattice or thin partition of deals, was put down the William Pit, and intended, by promoting a temporary circulation, etc., to assist the workmen in raising the clay and other matters which had been previously thrown down.

On the 19th of June, the water oozing out of the tubbing of the

William Pit, had risen to the height of twenty-four feet upon the clay. On the 3rd of July, this being all overcome, the brattice finished, and a great part of the clay drawn up, the sinkers began to bore a creep-hole out of the shaft into the north drift. On the next day, the stoppings in the tube drift of the John Pit were taken down, and the bore-hole finished, through which the air passed briskly into the mine, and ascended by the John Pit tube; and after a few days, the vapour issuing, which in the beginning took fire on the application of a candle, lost that property in consequence of the influx of atmospheric air.

Nine persons descended the William Pit, and as a current of water had been thrown down during ten hours, they found it practicable to traverse the north drift towards the plane-board, lighting their way by means of steel-mills. The shifts of men employed in this doleful and unwholesome search, were generally about eight in number; they were four hours in and eight hours out of the mine. The first body was found near the plane-board; and for a while the men stood over it in speechless horror, imagining that it was in such a state of decomposition that it would fall asunder in lifting into the coffin. At length they began to encourage one another "in the name of God," to begin; and after several hesitations and resolutions, and covering their hands with oakum to avoid any unpleasant sensation in touching the body, they laid it in a shell, which was drawn "to bank," on a bier constructed for the purpose. When the first shift of men came up, at ten o'clock, a message was sent for a number of coffins to be in readiness at the pit; these, being at the joiner's shop, piled up in a heap, to the number of ninety-two—a most gloomy sight!—had to pass Low Felling. . . .

Mr. Hodgson details with much minuteness the circumstances in which the bodies of the sufferers were respectively discovered—sometimes buried beneath the fall of the roof, but mostly lying exactly in the position in which they appeared to have been thrown at the moment of the explosion. In one place, twenty-one bodies lay together in ghastly confusion; some like mummies, scorched as dry as if they had been baked. One wanted its head, another its arm. The scene was truly frightful. The power of fire was visible upon all; but its effects were extremely various; while some were almost torn to pieces, there were others who appeared as if they had sunk down overpowered with sleep. At the bottom of the plane-board, the body of a mangled horse and four shattered waggons were found; the latter were made of strong frames of oak, strengthened with hoops and bars of iron, yet the blast had driven both them and the horse

with such violence down the inclined plane-board that it had twisted and shattered them, as if they had been shot from a mortar against a rock.

On the 19th September, the ventilation of the colliery was effected completely, and the workmen resumed their labours; but in little more than a year—namely, on the 24th December, 1813—another explosion occurred in the same mine, and killed twenty-three persons, and twelve horses; twenty-one individuals escaped, thirteen of whom were severely burnt. This explosion was certainly every way much less severe than the former; but as it happened when the morning shift of men were relieving the night shift, it might have been much more destructive than in fact it was; for a group of the fresh men were waiting to go down; and those who had just descended met the fatal whirlwind of fire in their way to the southern boards, which lie under the village of High Felling. That part of the mine was intersected with several dykes and fissures, which not unfrequently discharged great quantities of inflammable air, through the apertures called blowers, already described, and which made the small coals on the floor dance round their orifices, like gravel in a strong spring. Whether this accident was attributable to the falling of some matter so as to prevent the regular ventilation of the wastes, or to some neglect of the standing orders at the rarifying furnace in the upcast pit, could not be satisfactorily discovered; but so powerful was the stream of fresh air in all the workings, that the persons employed were unanimous in declaring that they never wrought in a pit so wholesome and pleasant.

The same author also records another and even more serious disaster at Wallsend—

On the afternoon of June 18th, 1835, an explosion of inflammable gas took place in the works of what is called "the Church Pit," in the Wallsend Colliery, by which one hundred and one human beings—about three-fourths of them boys—were suddenly hurried into eternity. It is unnecessary to go into the details of this appalling calamity; it may, however, be remarked that the works, which had been regularly inspected in the morning by the "under viewers," were considered in every respect safe and secure; so that whether the accident is to be referred to some of the miners having incautiously removed the head of their safety lamps, or to some other cause, will probably ever remain a mystery; as four persons—all who were saved—can give no account of the affair. Several of the bodies were black, shrivelled and burnt; one or two were mutilated; but the greater number, as

commonly happens in these cases, having been suffocated by the stythe, or afterdamp, had the appearance of being in a tranquil sleep. It appeared, indeed, from evidence offered on the Coroner's inquest, that by far the greater part of the sufferers had deliberately left the spot where they were at work, on hearing the explosion, and would in all probability have been saved, had not the fire-blast blown down various matters, so as to obstruct ventilation and ascent by the main shaft; and thus the victims perished by unexpected suffocation when fleeing for their lives. In 1821, there was an explosion in the same colliery, by which fifty-two lives were lost.

Observations

The above reports bring out several points of interest. First, with regard to the Felling explosion in 1812, there is mention of the great coal-dust clouds, without, however, any suspicion of the really dangerous nature of coal-dust. Secondly, the human side is described fully—a serious yet perhaps desirable omission from all modern reports. Thirdly, the use of the sparks from the Spedding mill for giving light in the presence of firedamp is mentioned, as well as the effect of blackdamp in giving the sparks a blood-red colour. Fourthly, the early attempts at rescue work are indicated, and the fires produced in the mine by the explosion are described. Fifthly, the closing of the shafts to extinguish the fire is detailed, and also the subsequent re-opening. Sixthly, the final recovery work by rescue teams of "about eight in number," working "four hours in and eight hours out of the mine," is mentioned, and from the description of how the bodies were lying one is able to gather that most of the men had been poisoned by the carbon monoxide of the afterdamp. The enormous violence of the explosion is also indicated.

The second explosion at Felling in 1813 is of interest mainly on account of the fact that "the persons employed were unanimous in declaring that they never wrought in a pit so wholesome and pleasant." In other words, the ventilation was far better than the average. The explosion was clearly a coal-dust explosion, and the purity of the ventilation (from

blackdamp) would be no safeguard, but rather a handicap, in this respect.

The same remarks apply to the description of the disaster at Wallsend Colliery in 1835—it will be seen that safety lamps had been introduced before 1835—but there is the additional information that "by far the greater part of the sufferers had deliberately left the spot where they were at work, on hearing the explosion, and would in all probability have been saved had not the fire-blast blown down various matters" (probably doors, timbers, air-crossings) "so as to obstruct ventilation and ascent by the main shaft."

This emphasizes the need of the training of rescue brigades in the work of hastily repairing and re-opening roadways, rebuilding air-crossings, etc., damaged by an explosion. Such work is generally necessary when attempting the rescue of the survivors.

CHAPTER II

THE AIR

ELEMENTS, COMPOUNDS, ATOMS, MOLECULES, ETC.

Elements and Compounds. Chemical analysis indicates that the matter which goes to form the earth's crust and atmosphere is composed of about eighty *elements*, sometimes free or uncombined, sometimes chemically united or in bunches. An *element* is a substance which cannot be split up into two or more substances, and a *chemical compound* is a combination of elements, not just a mixture of them. Thus oxygen, nitrogen, copper and carbon are elements, whereas carbon dioxide is a chemical compound of two elements, carbon and oxygen. Water is similarly a chemical compound of hydrogen and oxygen, two gaseous elements. Air, on the other hand, is a mixture of elements and compounds, since there are present oxygen, nitrogen, carbon dioxide, and water vapour. Chemical compounds always have a constant composition, i.e. the elements are always present in exactly the same proportion by weight. The properties of a compound are generally not like those of its constituents, whereas the properties of a mixture are generally similar to those of the elements in it.

Atoms. When chemical reactions take place, it is noticed that it is always certain proportionate weights of the different elements which combine or interact. This has led to the conception of *atoms*. An atom is the smallest indivisible particle of an element which can take part in a chemical reaction.

Atoms are of minute size and are quite invisible even under the most powerful microscope. The atoms of some substances weigh more than those of others; and the hydrogen atom, being the lightest, its weight is taken as unity. When the atomic weights of oxygen, nitrogen, and carbon are given as

16, 14, and 12, we mean that the atoms of oxygen, nitrogen, and carbon weigh, respectively, 16, 14, and 12 times as much as the hydrogen atom.

Molecules. Certain chemical phenomena lead us to think that the atoms of some elements may occur in the free state alone, whereas in other elements there seem to be present two or more atoms in the smallest particles of the substance occurring free. To these small particles we give the name *molecules*. A molecule, therefore, consists of one or more atoms, and is the smallest portion of a substance that can exist in the free state. Most elementary gases contain two atoms per molecule, but argon has only one. All compound gases must, of necessity, contain at least two atoms per molecule, and it follows that such gases cannot have an atomic weight; an atom is by definition an indivisible unit, and compounds consist of at least two atoms. These gases, however, have a molecular weight, namely, the weight of their molecules compared with that of an *atom* of hydrogen. Thus the molecular weight of oxygen is $2 \times 16 = 32$; of hydrogen $2 \times 1 = 2$; of argon $1 \times 40 = 40$; of carbon dioxide (CO_2) $12 + 32 = 44$; of methane (CH_4) $12 + (4 \times 1) = 16$.

Density. The density of a gas is the number of times that gas is heavier than hydrogen, bulk for bulk. Certain observations led Avogadro, in 1811, to suggest that unit volume of any gas contained a certain constant number of molecules, i.e. the same number for any gas, provided the temperature and pressure were constant. This suggestion is substantially true. Hence the *density* of a gas is equal to the number of times its molecule is heavier than the hydrogen molecule; and as the hydrogen molecule weighs two units, the density of any gas is equal to its molecular weight divided by two.

The **specific gravity** of a gas is the number of times it is heavier than air, bulk for bulk, and since air has a density of 14·5, the specific gravity of a gas is equal to its density divided by 14·5.

Note. For chemical calculations it is more convenient to regard the weight of the hydrogen atom as 1·008 instead of 1.

This alters the atomic weight of oxygen to exactly 16. The slight discrepancy thus introduced is negligible for most purposes. A list of the elements and their atomic weights is given at the end of this book.

Symbols. Each element is given a *symbol*, which strictly refers to the atom of the element if written alone. Thus, N represents one nitrogen atom, but N_2 represents one nitrogen molecule. The symbols of the elements and the formulae of the compounds, e.g. CH_4 for methane, CO for carbon monoxide, and CO_2 for carbon dioxide, are often used, however, as a convenient and expressive " shorthand " for the full written name, without any reference to the amount involved.

Chemical Reactions are indicated by chemical equations. Thus $C + O_2 = CO_2$ means that one atom of carbon combines with two of oxygen to form one molecule of carbon dioxide. It also shows that twelve parts by weight of carbon unite with thirty-two parts by weight of oxygen to form forty-four parts by weight of CO_2, the atomic weights of carbon and oxygen being 12 and 16.

The Earth's Atmosphere: Physical

The Pressure of the Air. The earth is roughly a sphere of about 4,000 miles radius. At the poles the diameter is 7,899·1 miles, at the Equator 7,925·6 miles; the highest mountains ascend nearly six miles, and the ocean does not seem to be more than about six miles deep in any part. These are but slight variations on a radius of about 4,000 miles.

The deepest mines in Great Britain are about three-quarters of a mile down, and the deepest mines in the world are only about one mile below the surface.

Surrounding the earth is an envelope of gases, several miles thick, called the *air*, or *atmosphere*, held to the earth by gravitational force. In other words, the gases of the atmosphere —like any other form of matter—have weight, and therefore exert a pressure on the earth's surface. This pressure is equal to the weight of the column of air vertically above. The height of such an air-column is less at the top of a mountain

than it is at the foot, and the atmospheric pressure is consequently less at the top than at the foot. Similarly, the height of the air-column at the bottom of a pit-shaft is greater than at the surface, and the atmospheric pressure is therefore greater in a mine than it is at the surface.

Barometric Pressure. At sea-level, the atmospheric pressure is on an average about 14·7 lb. per sq. in., and since 1 cub. in. of mercury weighs 0·49 lb., the pressure of the air can be balanced against a column of mercury $\left(\frac{14·7}{·49} =\right)$ 30 in. high. This is done by means of a barometer, which is simply a device for balancing the air column against a mercury column. Any other liquid could be used instead of mercury, but difficulties would be encountered because of (1) the enormous size (height) of the instrument if the liquid were of average density —thus a water barometer would be about 34 ft. tall—and (2) the vapour pressure of volatile liquids.

On ascending or descending, the pressure of the air falls or rises at a rate which may be easily calculated for moderate heights or depths. Thus, at sea-level, the pressure of the atmosphere is about 14·7 lb. per sq. in., or 2,117 lb. per sq. ft. Now, at 60° F. (an ordinary temperature in Great Britain), and under the above pressure, 1 cub. ft. of air weighs 0·076 lb. Hence, the height of the "homogeneous atmosphere"—i.e. assuming the air not to thin out—is $\left(\frac{2117}{·076} =\right)$ 27,900 ft. nearly. But this is supported by 30 in. of mercury column; hence, 1 in. of mercury is equivalent to $\frac{27,900}{30} = 930$ ft. of air. In other words, the barometer will rise by 1 in. of mercury for every 930 ft. of descent, and fall by an equal amount for every 930 ft. of ascent.

This rule, however, applies only to depths or heights of less than one mile (say, 5,000 ft.) and then only approximately, as the figures are effected by alterations in the weight of a cubic foot of air (which is governed by the temperature and pressure): for greater depths or heights a more complicated rule is employed.

It must not be thought that the air is of uniform density

throughout. As one ascends the pressure becomes less, and the air virtually "thins out" or becomes rarefied. The barometric pressure at an altitude of 10,000 ft. is about 20 in. of mercury, so that, assuming for the moment constant temperature, 1 cub. ft. of air at sea-level would occupy $(\frac{30}{20} =)$ 1·5 cub. ft. at this height. It is the "rareness" of the air which causes mountain-sickness until the body becomes acclimatized.

Temperature of the Air. The air temperature, however, falls as one ascends, and this tends to compensate, though but slightly, for rareness due to pressure drop. Observations taken from aeroplanes show that the temperature decreases uniformly as one ascends through the "troposphere"—i.e. to a height of six or seven miles in latitudes of 50° to 55°, as in England. The rate of decrease is 3·5° F. for every 1,000 ft. of ascent. Above the troposphere, the temperature seems to be constant at −65° F. up to a height of twenty miles or more.

The air in a pit-shaft is generally in rapid motion and does not acquire the temperature of the rocks until it has passed through a portion of the mine. Its temperature, however, tends to increase in the shaft because of the increased pressure which it suffers as it descends, the increased pressure being due to the growing column of air above it. When any gas is compressed there is a rise in temperature—as is well known to all who have used a bicycle pump—and the air descending a shaft becomes warmed because of the compression which it suffers. Moreover, **Sir W. Galloway** has shown that if the compression be adiabatic—i.e. compression without friction and without transfer of heat to or from the surroundings—the temperature tends to rise about 1° F. for every 185 ft. of descent, or 3° C. for every 1,000 ft. Thus, assuming a surface temperature of 50° F., the temperature of the air at the bottom of a shaft 1,000 yds. deep would be at least 66° F., as the effects of friction and rock temperatures have not been considered.

Geothermic Gradient. As the air travels through the mine, its temperature approaches closely to that of the strata when

it has travelled about 500 yds. from the shaft, and at the face it may be somewhat higher, the oxidation of coal, timber and pyrites increasing its temperature. The temperature of the strata depends upon the depth of the mine and the *geothermic gradient*, i.e. the rate of increase of rock temperature with depth. The geothermic gradient of the Coal-Measure strata of Great Britain is 1° F. for every 60 ft. of descent below the line of constant temperature, which line is about 50 ft. below the surface. The temperature of the rocks above this line is affected by seasonal changes, but below it the rise, as stated above, is roughly 1° F. for every 60 ft. of descent. At 50 ft. down from the surface, the temperature is 50° F. or thereabouts, so that at any depth, D ft., the rock temperature, t ° F., is given by the expression

$$t = \left(50 + \frac{D - 50}{60}\right)$$

Thus, at a depth of 1,000 yds., the rock temperature in the coalfields of Great Britain is about 99° F., or slightly more than body temperature.

The geothermic gradient in the Cornish tin mines is 1° F. for every 100 ft. of descent ; and in some of the Rand mines in South Africa it is as low as 1° F. for every 250 ft. descent.

The Density of the Air or Weight of 1 Cubic Foot. Experiments show that at ordinary temperatures (60° F.) and pressures (30″ mercury) 1 cub. ft. of air weighs about 0·076 lb. It is often important in mining work, however, to know exactly the weight of 1 cub. ft. of air. This is governed by the temperature and the pressure, and the most reliable formula[1] appears to be

$$W_d = \frac{1{\cdot}3228 \times B}{(458{\cdot}4 + t)} \quad . \quad . \quad . \quad . \qquad (1)$$

where W_d = the weight in lb. of 1 cub. ft. of *dry* air

B = the barometric pressure in inches of mercury

and t = the temperature in degrees Fahr.

[1] See *A Review of Hygrometry in Mining Practice*, by Douglas Hay. *Trans. Inst. Min. Eng.*, Vol LXX, page 169.

The expression is derived from consideration of Boyle's and Charles's Laws, as follows—

It is found by actual experiment that at 32° F. and 29·92 in. mercury pressure, 1 cub. ft. of dry air weighs 0·0807 lb.

Hence, at 32° F. and B in. mercury pressure, 1 cub. ft. dry air weighs $\dfrac{0{\cdot}0807 \times B}{29{\cdot}92}$.

At t° F. and B in. mercury pressure, 1 cub. ft. of dry air weighs

$\dfrac{{\cdot}0807 \times B}{29{\cdot}92} \times \dfrac{458{\cdot}4 + 32}{458{\cdot}4 + t}$ which evaluates to $\left(\dfrac{1{\cdot}3228\,B}{458{\cdot}4 + t}\right)$ lb.

When the Centigrade scale of temperature is used, the expression becomes

$$W_a = \frac{0{\cdot}736 \times B}{273 + t} \quad . \quad . \quad . \quad . \quad (2)$$

Expressions (**1**) and (**2**) are slightly different from those more usually employed, but they are more accurate. A very convenient and reasonably accurate expression for most purposes, however, is

$$W_a = \frac{1\tfrac{1}{3}\,B}{460 + t} \quad . \quad . \quad . \quad . \quad (3)$$

t being in deg. F.

Where great accuracy is essential, it is necessary to make allowance for the water vapour present (see Chapter III), and for the various impurities, such as carbon dioxide, methane, etc., in mine air.

The Earth's Atmosphere: Chemical

Chemical Constituents of the Air. Ordinary outside air has a remarkably constant chemical composition, whether in town or country, at the seaside or in the hills. At great elevations its composition certainly does alter, the oxygen percentage being less, and oxides of nitrogen occurring in quite appreciable amounts; but at ordinary levels fresh air

consists of the following mixture of gases, present always in the same amounts—

Oxygen	20·93	parts by volume
Nitrogen, Argon, etc. .	79·04	,, ,, ,,
Carbon dioxide . .	0·03	,, ,, ,,
	100·00	,, ,, ,,

Water vapour may be present up to 2 or 3 per cent, by volume, as explained in Chapter II.

By weight, the proportions of the gases present are, approximately—

Oxygen	23·00	parts by weight
Nitrogen, etc. . . .	77·00	,, ,, ,,
Carbon dioxide . .	0·04	,, ,, ,,

Along with nitrogen in the air are always found certain other inert gases (argon, etc.), making up about 1 per cent by volume of the atmosphere. These gases interest only the chemical specialist and will not be discussed further, but their amounts will be included under the heading of atmospheric nitrogen.

The atmosphere, then, is a mixture of gases, and is not a chemical compound, and the proportions of the various constituents are maintained by several natural processes. Thus, while combustion and respiration tend to reduce the oxygen content, plant life tends to increase it ; and vice versa as regards the carbon dioxide content. In the air of the "stuffiest" room, the carbon dioxide content is less than 1 per cent, and the oxygen more than 20 per cent. In fogs the carbon dioxide in the outside air may rise to 0·1 per cent and the oxygen fall to 20·8 per cent ; but these limits are rarely attained. Before proceeding further, however, it will be well to review the main properties of oxygen, nitrogen, and carbon dioxide.

Oxygen, O. Atomic weight, 16. Molecular weight, 32.

Density, 16 (H = 1). Sp. Gr. (Air = 1) $= \frac{16}{14 \cdot 5} = 1 \cdot 11$

Oxygen is a colourless gas, without smell or taste: present in the atmosphere to the extent of 20·93 per cent by volume and 23 per cent by weight. It is found throughout Nature generally in combination with other elements, thus giving oxides. For example, sand, quartz and flint, are all silicon dioxide, SiO_2, generally called silica. Shales, clays ("bind," "metal," etc. of the miner) are silicates, mainly aluminium silicate hydrated, $Al_2O_3 . 2SiO_2 . 2H_2O$, being therefore combinations of oxygen, aluminium, silicon and hydrogen. Water is oxide of hydrogen, H_2O; and limestone is a compound of calcium, carbon and oxygen, $CaCO_3$, i.e. calcium carbonate. Chalk and marble have also this same composition, $CaCO_3$. The properties of oxygen as a gas in the free state, however, are more important for the mining student.

Oxygen is necessary for life, for combustion, for explosion. Pure oxygen may be breathed for hours without ill effects; indeed, often with advantage. Loss of consciousness occurs at once in an atmosphere devoid of oxygen, though it is possible to drop the oxygen content of air to half its normal proportion (i.e. to 10·5 per cent) before a man begins to notice the change, provided always that CO_2 is not present to the extent of more than 1 per cent or thereabouts. When the oxygen falls to 7 or 8 per cent, loss of consciousness may follow, and without much warning. Flame-lamps and candles are extinguished when the oxygen falls to about 17 per cent or 17·5 per cent, whether CO_2 be present or not. Moreover, a candle or lamp flame loses about 30 per cent of its lighting power for every drop of 1 in the percentage of oxygen, even though the flame be large due to its reaching out for oxygen. On the other hand, artificial increases in the proportion of oxygen present in the air cause the flames to have increased brilliancy, and in pure oxygen a glowing splint will burst into bright flame.

Oxygen is slightly soluble in water, 100 volumes of water dissolving at 0° C. nearly five volumes of oxygen, and at 20° C. about three volumes of oxygen, under a pressure of 30 in. mercury in each case.

Oxygen is often given in artificial respiration after suffocation, carbon monoxide poisoning, or the like. (See page 171.)

Perfectly dry oxygen, it may be noted, is by no means as chemically active as is the gas normally. Indeed, perfectly dry substances in general often exhibit little chemical activity.

Oxygen is prepared in the laboratory by heating red lead or mercuric oxide or potassium chlorate. In the last case a little manganese dioxide should be mixed with the chlorate to steady the action.

$$\underset{\text{potassium chlorate}}{2KClO_3} = \underset{\text{potassium chloride}}{2KCl} + \underset{\text{oxygen}}{3O_2}$$

The gas may be collected over water in the usual manner, and its properties examined.

According to the Coal Mines Acts, the air in the mine is not deemed to be satisfactory if it contains less than 19 per cent of oxygen by volume.

Liquid Oxygen and Liquid Air. If air is cooled and compressed highly, a stage is reached at which it turns liquid. Such liquid air contains about 50–70 per cent of oxygen, as oxygen liquefies more easily than nitrogen. Liquid air is a pale blue liquid—the bluer the colour, the richer in oxygen—which is stored in special thermos flasks. A temperature of $-119°$ C. is necessary to liquefy oxygen, and at $-119°$ C. the pressure required is 50 atmospheres, i.e. $50 \times 15 = 750$ lb. per sq. in. Liquid oxygen has a sp. gr. of 1·13, and can be attracted by a magnet. Liquid oxygen, or liquid air rich in oxygen, is used in certain quarrying operations along with charcoal and the like, to give a useful explosive. Liquid air explosives are not suitable for use in dusty or gassy mines, on account of the large flames produced; but liquid air is used in coal mines in certain breathing apparatus for rescue work in poisonous atmospheres (see Chapter XVI).

Nitrogen, N. Atomic weight, 14. Molecular weight, 28. Density, $(H = 1) = 14$. Sp. gr., $(\text{air} = 1) = 0·97$. Atmospheric nitrogen is noteworthy rather for what it does *not* perform than for what it *does*. Its principal function is to

dilute the oxygen of the air so that combustions, etc., are not too rapid. The nitrogen of the air is present in molecular form (i.e. N_2) and this combination of two nitrogen atoms with each other apparently gives a very stable molecule. On the other hand, when nitrogen is combined with oxygen and with another substance or substances, to give nitrates (e.g. $C_3H_5(NO_3)_3$ = nitro-glycerine), the activity of the nitrogen atoms and the instability of the compound are most marked. Indeed, this fact is evident from the make-up of all high explosives, which consist always of compounds of nitrogen similar to the above. Nitrogen is about half as soluble in water as is oxygen. Nitrogen is an essential constituent of the proteid matter of all living organisms, animal or vegetable.

Nitrogen may be prepared by passing air slowly through a long iron tube containing copper turnings heated to redness. The copper combines with the oxygen to form copper oxide —a black powder or film -whereas the nitrogen is unaffected and may therefore be collected at the outlet end of the tube. Such nitrogen contains rather more than 1 per cent of argon, etc. Pure nitrogen may be obtained by heating ammonium nitrite, NH_4NO_2, the reaction being indicated by the equation

$$\underset{\text{ammonium nitrite}}{NH_4NO_2} = \underset{\text{water (steam)}}{2H_2O} + \underset{\text{nitrogen}}{N_2}.$$

Carbon Dioxide, CO_2. Molecular weight = 44. Density = 22 (H = 1), Sp. Gr. = 1·53 (air = 1). This gas is present in fresh air only to the extent of 0·03 per cent by volume, or 0·04 per cent by weight. It is the gas produced by animal respiration, and by the burning of substances containing carbon. The green colouring matter (chlorophyll) of plants, however, absorbs carbon dioxide under the influence of sunlight ; and water dissolves about its own volume of the gas at ordinary temperatures and pressures—i.e. 60° F and 30 in. mercury. In consequence of these facts, the proportion of carbon dioxide in the outside air does not increase. Indoors, with very bad ventilation, the proportion of carbon dioxide in the air seldom reaches 0·5 per cent, an amount

which has no noticeable effect on the breathing. It is not until the proportion of carbon dioxide rises to over 3 per cent that the effects begin to be felt, and headache produced, although with 1 or 2 per cent of the gas the breathing deepens. Men in submarines regularly breathe air containing up to 3 per cent of carbon dioxide, the air having been robbed of a corresponding quantity or rather more, of oxygen. A *deep* breath exhaled contains about 4 per cent (by volume) of carbon dioxide, 16·5 per cent of oxygen, and 79·5 per cent of nitrogen. A shallow or normal breath contains only about 2 per cent or less of carbon dioxide, so that exhaled air may be breathed again once without danger. The effects of carbon dioxide on a candle or lamp flame are discussed in a later chapter. In general, it is the shortage of oxygen which affects these flames rather than the presence of carbon dioxide.

Carbon dioxide is a heavy, colourless gas, with a faintly sharp smell and slightly acid taste. It does not support combustion. Its presence may be shown by its action on clear lime water from which it precipitates chalk, thus turning the lime water "milky." It is, however, absorbed best by caustic alkalis, such as caustic soda or caustic potash.

$$\underset{\substack{\text{caustic potash or}\\ \text{potassium hydroxide}}}{2KOH} + CO_2 = \underset{\substack{\text{potassium}\\ \text{carbonate}}}{K_2CO_3} + \underset{\text{water}}{H_2O}$$

Caustic soda (or potash) is therefore employed to absorb the CO_2 of the breath in breathing apparatus for rescue work, and also in air-analysis.

Production of Carbon Dioxide in Mines. In the mine, carbon dioxide is produced in large quantities by the oxidation of coal and timber, and in small quantities by the breathing of men and horses and the burning of lamps and candles. It is also given off from the coal and adjoining strata along with methane, in many firedamps, and occasionally as separate blowers of the gas. In the gob or waste, the small coal and timber are particularly subject to oxidation, the oxygen of any air there being absorbed and converted partly or wholly into carbon dioxide. This reaction, indeed, proceeds all

through the airways of the mine and gives rise to **blackdamp**, which is a mixture of nitrogen and carbon dioxide, containing as a rule from 5 to 20 per cent of the latter. Blackdamp is therefore air from which the oxygen has been absorbed and replaced to some extent by carbon dioxide. Blackdamp is naturally extinctive to flames and will not support life.

The mine air, according to the Coal Mines Act, 1911, must not contain more than 1·25 per cent of CO_2. This may seem but a small quantity in view of the comparative harmlessness of air containing, say, 2 per cent of the gas; but it is not difficult to ventilate the mine so as to keep the proportion of CO_2 below this figure, and the enforcement of the 1·25 per cent limit has doubtless resulted in better ventilation underground. The same remarks apply to the lower limit of 19 per cent for the oxygen content of the mine air.

Amount of CO_2 in Return Air. It is useful at this stage to realize the importance of even small proportions of CO_2, etc., in the return air. Thus, assuming that the quantity of air passing through the mine is 200,000 cub. ft. per min. and that the "return" contains 1·03 per cent of CO_2, i.e. 1 per cent more than in fresh air, the CO_2 produced per minute is 2,000 cub. ft. Also, since 1 cub. ft. of air weighs about 0·076 lb., and CO_2 is 1·53 times as dense as air, the weight of CO_2 produced is $2{,}000 \times 0{\cdot}076 \times 1{\cdot}53 = 233$ lb. per minute, or $\frac{233 \times 60}{2240}$ $= 6{\cdot}2$ tons per hour, i.e. 150 tons per day. The amount of carbon removed from the mine in this way would be $150 \times \frac{12}{44}$ $= 41$ tons per day, a surprisingly large quantity. CO_2 is also found in afterdamps, i.e. the gases remaining in the mine after an explosion, but it is the carbon monoxide (CO), *not* CO_2, which causes the deaths by poisoning (see page 56).

Preparation of Carbon Dioxide. CO_2 may be obtained in the laboratory by burning carbon (charcoal or coke) in oxygen, but it is best prepared by pouring cold dilute hydrochloric acid on to marble or limestone chippings. The chemical

reaction which then takes place (in the cold) is indicated by the following equation—

$$\underset{\substack{\text{calcium carbonate}\\ =\text{ limestone or}\\ \text{marble}}}{CaCO_3} + \underset{\substack{\text{hydrochloric}\\ \text{acid}}}{2HCl} = \underset{\substack{\text{calcium}\\ \text{chloride}}}{CaCl_2} + \underset{\text{water}}{H_2O} + \underset{\substack{\text{carbon}\\ \text{dioxide}}}{CO_2}$$

The CO_2 liberated may be collected over water or by displacement of air. CO_2 being 1·53 times as heavy as air, it will displace air out of an open jar if the CO_2 be led to the bottom of the jar by means of a tube.

CHAPTER III

WATER VAPOUR IN THE AIR

HYGROMETRY

The study of *hygrometry*, i.e. the measurement of the proportion of water vapour present in the air, becomes of greater and greater importance to the mining student as mines become deeper. It has been stated on page 13 that the rock temperatures in the Coal-Measure strata of Great Britain increase by 1° F. for every 60 ft. of descent below a line 50 ft. down from the surface, and that the temperature on this line is about 50° F. At a depth of 1,000 yds. the rock temperature is about the same as that of the body (98·5° F.) and the air of a mine becomes warmed to the rock temperature or thereabouts when it has travelled over a quarter of a mile from the downcast. Now, in hot, moist air, the body temperature rises, the pulse rate goes up, and collapse may soon follow due to heat stroke; in warm (80° F.) moist atmospheres the effects are similar but not so severe.

Hygrometry is also of importance to the mine manager, because large amounts of water vapour in the return air may indicate a gob-fire outbreak; and the drying effects of the cold winter air on the coal dust of the mine (especially near the downcast) may be of importance in rendering the mine dust more dangerously explosive.

Evaporation and Saturation. In ordinary outside air there is always present a small quantity of water vapour, generally from 1 to 2 per cent by volume. The quantity, however, is very variable and depends upon a number of conditions, the chief of which is the temperature. In cold weather, there can only be but little water vapour present, whereas in warm weather there may be 2 per cent or more. This will be explained presently.

Water is continually evaporating from rivers, ponds, seas,

etc., and the rate at which it evaporates, or *goes to vapour*, increases as the temperature rises. Consider a closed vessel containing air and a little water. On thorough agitation the air, or space, rather, will become saturated : in other words, a state will soon be reached when no more of the liquid can go to vapour. (Actually, it is not easy to saturate perfectly any space with water vapour in this manner.) If the vessel be warmed, however, a little more water goes to vapour, and if the heating be continued the evaporation proceeds further and further as the temperature rises. At any given temperature a certain saturation point can be reached when no more evaporation can take place. The quantity of water vapour present at saturation depends only on the temperature ; the pressure of the air is of no moment. Hence, the *presence* of the air is of no moment, for when the pressure is reduced to a very small amount, there exists for all practical purposes a vacuum, except for the water vapour. It is not true, therefore, to say that the " air absorbs water vapour " or " has the property of picking-up moisture," and so forth, though such statements are often made to facilitate the treatment of the subject. The important facts to realize are, (1) that the water vapour is present because of the tendency of water to evaporate, whether any air be present or not, and (2) that the amount of water vapour required to saturate any particular volume (of air or of vacuous space) depends only upon the temperature. It may be noted, in passing, that the *rate* of evaporation is a different matter altogether, and depends upon the temperature, the pressure, and the movements of the air and of the liquid.

The amount of water vapour present in the air may be expressed in grains per cub. ft. or in pounds per 1,000 cub. ft., which values are easily convertible one to the other, since 1 lb. = 7,000 grains. The amounts of water vapour present at saturation at different temperatures are given in the second and third columns of Table I, page 25, and plotted graphically in Fig. 1.

It will be observed that at 80° F. the moisture present for

saturation is nearly four times that present at 40° F., and at 90° F. it is nearly five times the amount present at 40° F.

Pressure of Water Vapour. It is generally simpler to consider the pressure of the aqueous vapour rather than the weight present in a given volume. If a small quantity of water vapour is introduced into a vessel previously evacuated, the vapour will expand and fill the vessel and then exert a

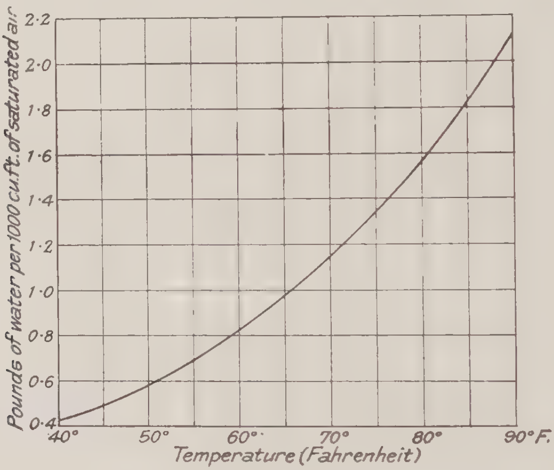


FIG. 1

certain pressure. If more vapour be introduced the pressure will rise, but only to a certain amount at any definite temperature, any further vapour introduced condensing to liquid. At this stage complete saturation is reached, and the pressure of the vapour is called its saturation pressure at the particular temperature. At the boiling point of water, 212° F., the vapour pressure is equal to that of the atmosphere, namely, 30 in. of mercury, or 14·7 lb. per sq. in. In the last column of Table I are given the saturation pressures in inches of mercury column for ordinary mine temperatures.

The relation between G, the grains of water vapour per cubic foot (i.e. the weight of 1 cub. ft. of saturated vapour),

and p, the saturation pressure in inches of mercury, is given by Marvin[1] as

$$G = \frac{11{\cdot}7449\,p}{1 + 0{\cdot}002037\,(t - 32)}$$

where t is the temperature in degrees Fahrenheit.

The values have been found by careful experiments, the principles of which may be demonstrated by introducing a little water into the mercury of a barometer. The water will rise to the top of the barometer and its vapour will then depress the mercury by about 0·247 in. at 40° F. (Table I), 0·360 in. at 50° F., and 0·517 in. at 60° F., as compared with the height of the mercury in a dry barometer standing alongside. The temperature of the upper halves of both barometers can be controlled by enclosing them in a water-jacket for the top 15 or 20 in.

TABLE I

Temperature ° F.	Grains of water vapour per cubic foot	Lbs. of water vapour per 1,000 cubic feet	Vapour pressure in inches of mercury
25	1·551	0·222	0·130
30	1·935	0·276	0·164
35	2·366	0·338	0·203
40	2·849	0·407	0·247
45	3·414	0·488	0·298
50	4·076	0·602	0·360
55	4·849	0·693	0·432
60	5·745	0·821	0·517
65	6·782	0·969	0·616
70	7·982	1·140	0·732
75	9·356	1·337	0·866
80	10·934	1·562	1·022
85	12·736	1·819	1·201
90	14·790	2·113	1·408
95	17·124	2·446	1·645
100	19·966	2·824	1·916

Precautions where Accuracy is Required. For very accurate barometric measurements, the observed height of the mercury must be corrected for temperature effects, the mercury being

[1] *Psychrometric Tables*, U.S.A. Dept. of Agriculture.

less dense when warm because of its expansion. The expansion of the measuring scale must also be allowed for, as well as any diminution or increase in the apparent value of gravity due to differences in latitude and also in the distance from the earth's centre ; and allowances have to be made for the vapour pressure of the mercury in the " vacuum " at the top of the barometer, and perhaps for capillarity. The accurate use of the barometer is, therefore, no simple matter.

Finally, it should be noted that the pressure indicated by the barometer is the joint pressure of the dry air and of the water vapour present. Thus, if the air were *saturated* at 50° F., and the barometer read 29·96 in., the actual pressure of the air (dry) is $29 \cdot 96 - 0 \cdot 36 = 29 \cdot 60$ in. of mercury column, 0·36 being the pressure of water vapour at saturation at 50° F.

Relative Humidity. In most circumstances, however, the air is not saturated. Indeed, it is only at the *dew point*, i.e. when moisture is being deposited as mist or dew, that complete saturation obtains. In all other conditions the air is only partially saturated. If the air, or space, rather, is holding half its full quota of water vapour, it is said to be 50 per cent saturated, or to have a relative humidity of 50 per cent. Thus, at 50° F., if the vapour pressure were 0·180 in. mercury and the moisture content consequently 2·038 grains per cub. ft., the space would be 50 per cent saturated, i.e. $\frac{\cdot 180}{\cdot 360} \times 100$ or $\frac{2 \cdot 038}{4 \cdot 076} \times 100 = 50$. But if the temperature were 40° F. and the vapour pressure were still 0·180 in. mercury, the percentage saturation would be $\frac{0 \cdot 180}{0 \cdot 247} = 73$ per cent.

Now, imagine 1 cub. ft. of moist air at a pressure of B in. of mercury and temperature $t°$ F., and let p in. of mercury denote the pressure exerted by the water vapour present. Observe that p will not normally be the saturation pressure of water vapour at temperature $t°$ F. There exists, then, 1 cub. ft. of dry air at a pressure of $(B - p)$ in. of mercury, and

temperature t; and also 1 cub. ft. of water vapour at a pressure p and temperature t.

The mass (or weight) of the cubic foot of dry air is $W_d = \left(\frac{1{\cdot}3228 \times (B-p)}{458{\cdot}4+t}\right)$ lb., as shown earlier. The mass of the water vapour, m, is $0{\cdot}622 \times \left(\frac{1{\cdot}3228 \times p}{458{\cdot}4+t}\right)$ lb., since 1 cub. ft. of water vapour at any temperature and pressure has 0·622 times the weight of 1 cub. ft. of air at the same temperature and pressure. In other words, aqueous vapour is only 0·622 times the weight of air, at the same temperature and pressure, bulk for bulk. The total weight W_m of 1 cub. ft. of air containing water vapour is then $(W_d + m)$, i.e.

$$\left(\frac{1{\cdot}3228 \times (B-p)}{458{\cdot}4+t}\right) + \left(\frac{0{\cdot}622 \times 1{\cdot}3228 \times p}{458{\cdot}4+t}\right)$$

Hence, $$W_m = \left(\frac{1{\cdot}3228}{458{\cdot}4+t}\right) . (B - p + 0{\cdot}622\,p)$$

or $$W_m = \left(\frac{1{\cdot}3228 \,.\, (B - 0{\cdot}378\,p)}{458{\cdot}4+t}\right) \text{lb.} \qquad (4)$$

This expression is employed where great accuracy is required. It has still to be shown, however, how to find the value of p, the pressure of the aqueous vapour present.

Hygrometry. There are several means of measuring the vapour pressure, p, one simple method being simply to cool down a smooth surface till dew is deposited on it, note its temperature at this dew-point, and then find from Table I the saturation pressure corresponding to such dew-point. Thus, assuming the air temperature were 60° F. and the dew-point 40° F., the pressure of the aqueous vapour is 0·247 in. of mercury, and the percentage saturation is $\frac{0{\cdot}247}{0{\cdot}517} = 47{\cdot}8$ per cent, 0·517 in. of mercury being the saturation pressure at 60° F.

The usual method in mines, however, is not to use a dew-point hygrometer, but a combination of two thermometers, known as a wet and dry bulb hygrometer (Fig. 2).

Wet and Dry Bulb Hygrometer. In this instrument, one of the thermometers has its bulb open to the air and the other has its bulb covered with a piece of thin wet muslin cloth, which dips into a small water reservoir underneath. The air blows on both thermometer bulbs, but the wet bulb thermometer always reads lower than the dry, because of the cooling effect of the evaporation taking place at the wet bulb.

Whenever water evaporates, it takes in latent heat to the extent of, roughly, 1,000 B.Th.U. per pound of water evaporated. Consequently, the drier the air, or the more rapidly evaporation takes place from the wet bulb covering, the greater will be the depression of the mercury level in the wet bulb thermometer stem. Also, the more rapidly the air is moving the greater will be the cooling effect due to evaporation at the wet bulb. In practice, however, it is found that if the air be passing at about 8 ft. per sec. (say 500 ft. per min.) any increase in speed produces no appreciable lowering of the wet bulb temperature. In the mine, therefore, the hygrometer is exposed to rapidly moving air when a reading is desired. If the air is moving slowly, the hygrometer should be wafted about, or it may be mounted on a suitable frame and handle to enable the observer to whirl the instrument in the air, e.g. Storrow's whirling hygrometer (see Fig. 2).

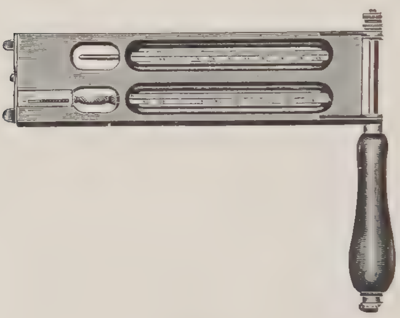


FIG. 2

If the air is saturated, both thermometers will read the same. If not, the readings are taken and the hygrometric state of the air—dew-point, vapour pressure, and relative humidity—found from reference to tables such as Marvin's. Glaisher's tables are often used, but they are none too accurate and are not relied upon in Continental countries and America.

When it is very cold and the temperature given by the wet bulb thermometer is below 32° F., the water may still remain liquid in the reservoir. This is immaterial, provided that a steady consistent reading is obtained after successive whirlings of half a minute. But if the water suddenly freezes, the heat of fusion is given out, the temperature of the wet bulb becomes 32° F., and the bulb then becomes covered with ice. This, again, is immaterial, provided enough time is allowed for the ice formation, and also that successive readings are taken until the minimum wet bulb temperature is obtained.

The Wet Bulb Temperature and the Human Body. Drs. Haldane, L. Hill, and others, have shown that the relative humidity is not of very great significance as a measure of the suitability or otherwise of the atmosphere for work as far as the human body is concerned. A far more useful guide is simply the wet bulb temperature. The human body, when in perspiration, may be likened to the wet bulb of the thermometer, and if the air is too warm and moist to maintain the mercury of the wet bulb below 85° F., the air is then too warm and moist to carry away quickly enough the heat and moisture given off by the body, and serious conditions arise. The pulse frequency increases, the temperature of the body rises, and heatstroke and collapse may follow. In places such as the Black Hole of Calcutta the victims undoubtedly died from heat-stroke due to the hot, moist atmosphere of their cell rather than from any shortage of oxygen or presence of carbon dioxide. On warm, " clammy " days, the general feeling of depression is well known, but it is not sufficiently realized that much of this may be obviated simply by improving the ventilation by fans or the like ; for the air, though moist on such days, is never saturated, and the cooling of the body can easily be promoted by causing the air to circulate. In the mine also, the problem generally resolves itself into increasing the ventilation in the hot, moist districts, though cooling of the air by water-sprays or refrigerating plant has sometimes to be adopted.

Moisture Removed from the Mine by the Ventilating Current.

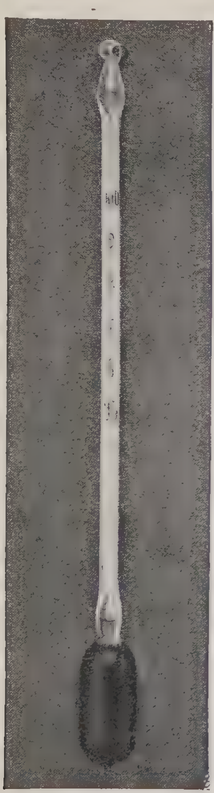
A large quantity of moisture is removed by the ventilating current from all mines in the winter. This may explain to some extent the occurrence of large mine explosions in the winter rather than in the summer. Assuming that the cold winter air at, say, 35° F., is 50 per cent saturated, and that the return air (from a deep mine) is at a temperature of 80° F., and 80 per cent saturated, and that the intake air passing for ventilation is 100,000 cub. ft. per min., it is easily seen that the amount of moisture taken into the mine per minute is $\left(33{\cdot}8 \times \frac{50}{100}\right) = 16{\cdot}9$ lb. (Table I). On leaving the mine, the volume of return air will be about $100{,}000 \times \left(\frac{458{\cdot}4 + 80}{458{\cdot}4 + 35}\right)$ $= 109{,}000$ cub. ft. per min., and the weight of water vapour $109 \times \frac{80}{100} \times 1{\cdot}562 = 136{\cdot}2$ lb. carried per minute.

Hence, the weight of moisture removed *per minute* is $(136{\cdot}2 - 16{\cdot}9 =)$ $119{\cdot}3$ lb., or 7,158 lb. per hour. This is about 3·2 tons per hour, or 77 tons per day.

Now, many modern mines pass three or four times the above quantity of air per minute, so that it is easily possible for the ventilating current to remove moisture from deep mines in the winter at the rate of ten tons per hour, and the drying effect must therefore at this time of the year be considerable. This moisture, needless to say, does not come mainly from human beings and animals in the mine, but almost entirely from the oxidation of coal, timber and the like in dry mines, and also from the strata in wet mines.

The Hygrometer as an Indicator of Gob Fires. It will be shown in a later chapter that one of the earliest indications of a gob fire is "sweating of the strata." This is merely the condensation of moisture from the heating coal on the comparatively cool sides, roof, and floor of the mine roadways. In a sense, it is the deposition of dew from the gob fire. Hygrometer readings, if taken regularly, should anticipate such an occurrence; higher dry and wet bulb temperatures will be noticed, and the manager consequently forewarned of the danger.

Coal Mines Act. According to the Coal Mines Act, 1911, hygrometers must be read in the mine daily in the main intake airways near the bottom of the downcast shaft, and



Dry Kata

Wet Kata

FIG. 3. KATA THERMOMETER

weekly in the main return airways. A record must be kept of the readings.

The Kata Thermometer. Before leaving the subject of health and the nature of the underground ventilation, attention must be given to the Kata thermometer. This instrument was devised by **Dr. Leonard Hill** to measure the cooling

power of the air on the human body. It can also be used to measure the velocity of the air if the temperature of the air is known. The Kata thermometer consists of a special alcohol thermometer with a large bulb, the thermometer stem having two marks corresponding to 95° F. and 100° F. The temperature of the human body is about 98·5° F., and skin temperature about 97·5° F. Consequently, the temperature range of the Kata thermometer covers 2·5° F. above and below that of the skin. To use the instrument, the bulb is warmed, generally in a little warm water, until the alcohol in the thermometer is beyond the 100° F. mark and has begun to enter the trap at the top. The bulb is then wiped dry, and the instrument placed in the air whose cooling power it is desired to find. The time in seconds is now taken for the alcohol level to fall from the 100° to the 95° mark. This is divided into a factor marked on the back of each instrument, and a value for the cooling power (H) of the air is thus obtained. The cooling power is obviously greater the less the time required : hence, the reason for dividing the factor by the time interval. The cooling power is actually given in millicalories per square centimetre per second, but the *relative*, not the absolute, value of the results is the important matter. The cooling power should not be less than 5 or 6 for normal surface work.

To find the velocity of the air, the air temperature t° F. must be taken by another thermometer. The velocity of the air may then be found from tables or calculated from the following formula—

Let $97{\cdot}7 - t = \theta$, and V = velocity of air in feet per minute.

Then, if $\dfrac{H}{\theta}$ is less than 0·33, $\quad V = \left(\dfrac{H/\theta - 0{\cdot}11}{0{\cdot}016}\right)^2$

and if $\dfrac{H}{\theta}$ is greater than 0·33 $\quad V = \left(\dfrac{H/\theta - 0{\cdot}072}{0{\cdot}019}\right)^2$

H being the cooling power as defined above.

The Kata thermometer is sometimes employed as a wet

Kata, i.e. the bulb is covered with a muslin glove finger and the instrument employed as usual, dipping the bulb and glove finger into warm water at the start, but only shaking off any large drops of water before actual use in the air. The values obtained are perhaps more comparable to the cooling effects of the air on the clothed, perspiring, human body than are those of the dry Kata ; but further research seems necessary before any definite conclusion can be drawn.

CHAPTER IV

FLAME, COMBUSTION, AND OXIDATION

Flame. Oxidation, in the simplest meaning of the term, denotes combination with oxygen. Oxidation differs from combustion in that flame does not necessarily, nor even usually, accompany many oxidation processes, whereas it is essential to true combustion. Again, combustion may occur without oxidation as when iron or copper burns in chlorine. Combustion in air, however, is invariably oxidation with the accompaniment of flame.

Flame may be regarded as the outcome of the rapid combination of gaseous particles, the heat developed being sufficient to raise their temperature to the point of incandescence. Apparently, when certain reactions giving out heat occur rapidly in gases and vapours, heat and light vibrations (radiations) are set up, which affect the eye, and a flame is seen.

A candle flame or lamp flame consists of three main portions, (1) the inner, non-luminous zone, in which there are combustible gases but little or no combustion; (2) the luminous zone, in which combustion has started; and (3) the thin outer, non luminous zone or envelope in which the combustion is completed. The luminosity of a flame is thought to be due either to incandescent (solid) carbon particles or to incandescent vapours. The temperature in a lamp or candle flame is well over 2,000° F. (1,100° C.). A Bunsen flame is non-luminous, because air is mixed with gas before the (explosive) mixture is burned; and the diluting action of the nitrogen of the air now exerts more influence on the inner portions of the flame.

Combustion. When a candle burns, the carbon (C) and hydrogen (H) of which the wax is composed combine with the oxygen of the air to form carbon dioxide (CO_2) and steam (H_2O).

$$C + O_2 = CO_2$$

$$2H_2 + O_2 = 2H_2O$$

The wick serves merely as a means of bringing the wax into a molten condition and gasifying or vaporizing it, so that the wax may be burned steadily and usefully as a source of light. The wick itself is consumed, of course, as the candle burns down, and its combustion is similar in essentials to that of the candle wax. The same process is involved in the combustion of oil in an ordinary lamp, except that the fuel does not require melting, the oil being drawn up the wick by capillary attraction.

The combustion of coal in some aspects is intricate, but viewed broadly the process again consists essentially in the combustion of carbon to CO_2 and the combustion of hydrogen to H_2O. These two chemical reactions, therefore, are of great importance ; they are practically the only combustions commonly employed for developing heat and light ; in other words, all common fuels consist mainly of carbon and hydrogen.

Now, when carbon combines with oxygen to form CO_2, the proportions of carbon and oxygen which combine are always the same. This is nothing exceptional ; it is typical of all chemical reactions. Thus, 1 lb. of carbon combines always with $2\frac{2}{3}$ lb. of oxygen to form $3\frac{2}{3}$ lb. of CO_2. Similarly, 1 lb. of hydrogen unites always with 8 lb. of oxygen to form 9 lb. of H_2O.

Heat of Combustion. When 1 lb. of carbon burns to form CO_2, there is liberated always a definite quantity of energy which appears as heat ; and it is this heat of combustion of carbon which is utilized commercially in the burning of most fuels. Thus, 1 lb. of C in burning to CO_2 ($3\frac{2}{3}$ lb.) gives out enough heat to raise the temperature of 14,600 lb. of water through 1° F. In other words, it evolves 14,600 British Thermal Units (B.Th.U.), or the *calorific value* of carbon is 14,600 B.Th.U. per lb. This may be written

$$C + O_2 = CO_2$$
$$1 \text{ lb.} + 2\tfrac{2}{3} \text{ lb.} = 3\tfrac{2}{3} \text{ lb.} + 14{,}600 \text{ B.Th.U.}$$

If the oxygen (or air) supply be limited, however, carbon monoxide (CO) is formed, generally with some CO_2. If CO

alone be produced, only 4,400 B.Th.U. are evolved per lb. of carbon.

$$2C + O_2 = 2CO$$

$$1 \text{ lb.} + 1\tfrac{1}{3} \text{ lb.} = 2\tfrac{1}{3} \text{ lb.} + 4{,}400 \text{ B.Th.U.}$$

In open combustion, with plenty of air, little or no CO is formed unless the conditions are peculiar.

When *hydrogen* burns, the heat evolved is 62,100 B.Th.U. per lb. of hydrogen burnt to H_2O. Thus, we may write

$$2H_2 + O_2 = 2H_2O \text{ (water)}$$

$$1 \text{ lb.} + 8 \text{ lb} = 9 \text{ lb. water} + 62{,}100 \text{ B.Th.U. (gross).}$$

This assumes, however, that the steam formed is condensed to water and evolves heat in the process. On the other hand, if the steam produced remains as steam at 212° F., say, the heat liberated is less by 10,000 B.Th.U., 9 lb. of steam holding 9×966 B.Th.U. as latent heat, and $9 \times (212 - 60)$ B.Th.U. being present as sensible heat in the water formed on condensing. The equation then becomes

$$2H_2 + O_2 = 2H_2O \text{ (steam)}$$

$$1 \text{ lb.} + 8 \text{ lb.} = 9 \text{ lb. (steam)} + 52{,}100 \text{ B.Th.U. (net).}$$

The *gross calorific value* of hydrogen is therefore 62,100 B.Th.U per lb.; its *net value* 52,100 B Th.U. per lb.

When substances contain carbon and hydrogen, however, it is seldom that these elements are present in the free state, i.e. uncombined. Almost invariably they are united with each other and often with some other element such as oxygen. Now, when such compounds are formed from their elements, there is always an evolution or absorption of a certain quantity of heat; consequently, on combustion of the substance the heat given out is not, as a rule, the same as that which would have been given out if the C and H had not been combined. Thus, firedamp (CH_4) contains three-quarters of its weight as carbon and quarter as hydrogen. Hence, 1 lb. of methane might be expected to evolve on combustion $(\frac{3}{4} \times 14{,}600) + \frac{1}{4}(62{,}100) = 26{,}475$ B.Th.U., whereas experiment shows that 1 lb. of methane evolves only 23,513 B.Th.U., the difference

(2,962 B.Th U.) being the heat of formation of 1 lb. of firedamp CH_4. In other words, when $\frac{3}{4}$ lb. of carbon combines with $\frac{1}{4}$ lb. of hydrogen to form 1 lb. of methane, the heat evolved is 2,962 B.Th.U.

It will be observed, then, that firedamp, on burning or exploding in air, can liberate a certain maximum quantity of energy, roughly 23,500 B.Th.U. per lb. of CH_4. This energy is the cause of the violence of firedamp explosions in the mine. Considerations of the actual phenomena and of the pressure developed are given in Chapter VII. Similarly, when coal burns in air (or coal-dust explodes) there is a certain maximum amount of energy per pound of coal which can be developed, and it depends upon the calorific value of the coal. British coals have calorific values ranging from 10,000 to 16,000 B.Th.U. per lb., the coals with the lower values being those containing much ash and moisture. The calorific value of the pure dry coal (free from ash) lies between 14,000 and 16,000 B.Th.U. per lb., coals with 20 per cent of volatiles (see page 88) having the highest values [1], with the exception of cannels. The fact that bituminous coals of high volatile matter content (say 40 per cent) have generally a lower calorific value than those of less volatiles down to 15 or 20 per cent, may explain why the dusts of *certain* coals rich in volatile matter are not so violent on explosion as those containing less volatiles.

Slow Oxidation and Respiration. When substances combine with oxygen without the accompaniment of flame, they are said to undergo oxidation. If a piece of iron wire be heated and allowed to burn in oxygen, the combustion is complete in a few seconds; but if the iron is allowed to rust in air or oxygen, the complete oxidation may require several weeks. The same chemical change will occur and the *same amount of heat will be evolved*, but the time taken for the rusting process being so much longer, the heat production will probably take place unnoticed. Similarly, with the slow oxidation

[1] *Trans. Inst. Min. Eng.*, Vol. LXVII, pages 199–221, "The Calorific Values of Coals," by J. W. Whitaker.

of coal, wood, and pyrites which takes place in the mine, and gives rise to blackdamp and sometimes to gob fires if the heat is not carried away as it is produced (see Chapter XIV).

Ordinary Respiration or Breathing is a similar process. Air is taken into the lungs, and the oxygen is absorbed by the blood in the lung capillaries. It is the red colouring matter or haemoglobin of the blood which is the active absorbent.

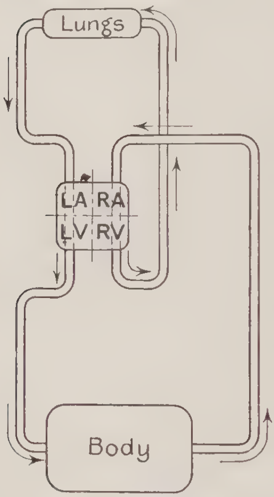


FIG. 4. CIRCULATION OF THE BLOOD

The blood charged with oxygen passes from the lungs to the left auricle of the heart, then to left ventricle, and thence to the main aorta or principal artery, the minor arteries and the capillaries. From the capillaries the blood returns through the veins to the right auricle of the heart, then to the right ventricle, and thence to the lungs, where it again becomes charged with oxygen, being purified from carbon dioxide in the process. The circulation, therefore, may be indicated diagrammatically by Fig. 4.

The blood, on leaving the lungs, begins to part with its oxygen and oxidize the tissues of the body, forming carbon dioxide from the carbon of the body and water from the hydrogen. The blood returning along the veins is therefore charged with CO_2, and is dark red to purple in colour, in contrast with arterial blood, which is bright red to scarlet.

In the lungs there is a thin membrane partition between the air in the lungs and the lung capillaries, and the CO_2 of the venous blood diffuses through this membrane into the air in the lungs while the air of the lungs diffuses in the opposite direction. (The capillaries are a network of vessels joining the minor arteries and veins.) The air in the lungs is thus renewed at each breath—but only partially—the percentage of carbon dioxide in the air cells (alveoli) of the lungs being

always about 5·6 (by volume) at ordinary atmospheric pressure. Expired air from a deep breath contains about 80 per cent nitrogen, 16 per cent of oxygen, and 4 per cent of carbon dioxide. As mentioned above, some of the oxygen inhaled has gone to produce water in the form of moisture in the breath, perspiration, etc. The amount of oxygen consumed per man per minute, and other details, are given on page 172, in the chapter dealing with "Breathing Apparatus."

Respiration, then, is essentially oxidation, the heat produced maintaining the body at a warm temperature, 98·5° F. At meal times fuel is taken in the form of food. When the body is working at hard manual labour, the heat production increases, but the temperature is maintained normal by perspiration, i.e. the cooling effects due to evaporation of moisture.

Prof. Moss[1] has found that in warm temperatures, when the body perspires freely, and thirst has to be satisfied frequently, considerable relief is experienced if a small quantity of common salt is used in the water, one teaspoonful in a gallon. According to Moss, the reason for this is probably that the blood requires its concentration of salt to be maintained, and as it loses salt in perspiration the loss should be made good. The drinking of pure water in the circumstances serves still further to reduce the concentration of salt, and tends to produce fatigue and cramp.

Extinctive and Irrespirable Atmospheres. A candle or lamp flame is extinguished when the oxygen content falls from the usual figure of 20·93 per cent to 17·5 per cent. The presence of other gases makes little difference. An acetylene flame, however, is not extinguished until the oxygen content is as low as 10 per cent, and a hydrogen flame will burn until the oxygen content is reduced to 7·5 per cent. On the other hand, reducing the oxygen content of the air has little effect on the respiration of men until a figure of about 11 per cent of oxygen is reached. Breathing then becomes deeper, and with further reduction in oxygen content to 5 or 6 per cent, the face becomes flushed and darkened, followed quickly by

[1] *Trans. Inst. of Min. Eng.*, Vol. LXVI, p. 284, and Vol. LXVIII, p. 364.

loss of consciousness and death. If, however, the shortage of oxygen is accompanied by the presence of an approximately equal volume of carbon dioxide, the effects on the human system are different. As soon as there is more than 3 per cent of carbon dioxide present, breathing becomes appreciably deeper and headache follows. With 6 per cent of carbon dioxide, the face becomes grey, and severe distress occurs, and with more than 10 per cent the gas acts as a narcotic poison, although the action is not very rapid. If the carbon dioxide is replacing both the nitrogen and the oxygen of the air, and not simply the oxygen, the physiological effects are not so severe as those stated above, and the action is far more delayed. The following table summarizes these statements—

TABLE II

EXTINCTIVE AND IRRESPIRABLE ATMOSPHERES

	Percentage		
	O_2	N_2	CO_2
Candle and lamp flames just extinguished	17·5	82·5 (N₂ + CO₂)	
Acetylene flames just extinguished .	10·0	90·0	
Hydrogen ,, ,, ,,	7·5	92·5	
Precarious to life (no CO_2 present) . .	10·0	90·0	nil
,, ,, ,, (CO_2 replacing O_2) .	16·0	79·0	5·0
,, ,, ,, (CO_2 replacing air) .	19·0	71·0	10·0
Fatal to life (no CO_2 present) . .	5·0	95·0	nil
,, ,, (CO_2 replacing O_2) . .	13·0	79·0	8·0
,, ,, (CO_2 replacing air) . .	17·8	67·2	15·0

Explosion. It has been seen that oxidation may take place slowly, as in the rusting of iron and the oxidation of coal, more quickly as in respiration, and still more quickly as in ordinary burning or combustion. The rate, however, may be yet more rapid; it may be almost instantaneous, in which case we have an explosion. To effect an explosion, provision should be made for intensely rapid combustion, and this is most easily done if the explosive substance is a gas, since the particles of one gas easily mingle with those of any other gas. It is consequently a simple matter to arrange for

a homogeneous mixture of combustible gas, such as firedamp, with air or oxygen.

For example, if we take 10 cub. ft. of air and add 1 cub. ft. of firedamp (methane), the gases will intermingle (see note on "Diffusion" at end of chapter) after a while, and on introducing a source of heat, such as a candle flame, a violent explosion will ensue. The methane molecules and the oxygen molecules, being in close proximity throughout, the combustion becomes instantaneous. A still more violent explosion would have occurred if we had taken 2 cub. ft. of oxygen and added 1 cub. ft. of methane, since the damping effect of the inert nitrogen molecules of the air would then have been absent. On the other hand, if we take 1 cub. ft. of methane in a cylinder provided with a small opening and a jet or tap at one end, and a piston at the other, then on pushing the piston a little and opening the tap, the methane can be expelled at the opening, where it may be lit with a candle flame. The methane will now burn steadily at the jet, as long as the piston is pushed gently along. In fact, it will burn in the same manner as ordinary town gas (coal-gas) lit at an open jet, and the flame will be fairly luminous (not blue) unless it is made very small by almost closing the tap. It is not every mixture of firedamp and air which is explosive ; but only those mixtures containing between 5·4 and 14·5 per cent of firedamp by volume. See Chapter V, page 53.

We may note here the approximate limits of inflammability in air of some of the commoner gases. The exact limits depend upon the conditions of ignition, size and shape of vessel, etc. The figures given in Table III are percentages by volume.

If the combustible substance is a liquid, it has to be either vaporized or sprayed into a mist of fine particles before it becomes explosive in air. This is effected by the carburettors of automobiles, etc.

If the combustible substance is a solid, it has to be converted into a powder and then raised as a cloud in air (or in oxygen) before it becomes explosive. Thus, clouds of flour dust or

sugar dust, or *coal dust* are violently explosive when ignited by a flame of sufficient intensity. The explosive nature of coal-dust clouds is now admitted by all mining engineers, though doubted by many in the last century. The preventive measures taken to avoid coal-dust explosions in the mine are the outcome of careful and extensive experiments carried out by Garforth, Wheeler and others. "Coal-dust Explosions" are discussed in Chapters VIII, IX, and X.

TABLE III

LIMITS OF INFLAMMABILITY IN AIR[1]

	Lower limit	Upper limit
Methane (CH_4)	5·4	14·5
Hydrogen (H_2)	6·1	71·4
Carbon monoxide (CO) . . .	16·3	71·2
Ethane (C_2H_6)	3·2	10·6
Ethylene (C_2H_4)	3·4	14·1
Coal gas (variable)	7	25

Explosives. The explosions enumerated above depend upon the rapid combustion of a substance (solid, liquid, or gas) with the oxygen of the air. But there is another method of making a combustible solid or liquid explode, and it consists in embodying the oxygen (necessary for the explosion) into the composition of the substance. The oxygen, however, must not combine directly with the substance, or the combustion will have taken place. The combination must be indirect and is generally effected through the agency of nitrogen atoms. Thus, if glycerine $C_3H_5(OH)_3$ be treated with nitric acid HNO_3, it may be converted to nitro-glycerine $C_3H_5(NO)_3$, a well-known liquid explosive. On shock or heat this substance can be suddenly decomposed and the oxygen atoms which hitherto were in combination with the nitrogen atoms (in the NO_3 groups) are liberated and immediately oxidize the C and H atoms to CO_2 and H_2O, producing at the same time a violent explosion. This type of explosion, however, is quite different from the foregoing types, inasmuch as no atmospheric air is necessary. The

[1] See Payman and Wheeler, *Fuel*, October, 1922, page 185.

difference is important, and will be referred to again in Chapter XII on "Explosives."

Diffusion of Gases. Gases diffuse into one another readily, the lighter gases diffusing most quickly. *Graham's Law of Diffusion* states that a gas diffuses at a rate which varies inversely as the square root of its density. The density of hydrogen is 1·0; of air, 14·4; of methane, 8·0; of CO_2, 22·0; of CO, 14·0; of H_2S, 17·0; of oxygen, 16·0; of nitrogen, 14·0. Hence, methane diffuses into air at a rate 1·414 times as quickly as that at which oxygen diffuses into air.

$$\frac{CH_4}{O_2} = \frac{\frac{1}{\sqrt{8}}}{\frac{1}{\sqrt{16}}} = \frac{\sqrt{16}}{\sqrt{8}} = \frac{1{\cdot}414}{1}.$$

In diffusion experiments the lighter gas is always placed above the heavier, in order to avoid the mechanical mixing which would otherwise be caused by gravity.

CHAPTER V

MINE GASES

THE gases peculiar to mines are blackdamp, firedamp, whitedamp, stinkdamp, and nitrous fumes from certain explosives.

Blackdamp. As indicated in Chapter II, blackdamp is essentially nitrogen mixed with 5 to 20 per cent of CO_2. It may be regarded as air from which the oxygen has been removed and replaced partly or wholly by CO_2. According to **J. I. Graham,** blackdamp from the simple oxidation of coal may be expected to contain 94 to 95 per cent of nitrogen, 5 per cent of CO_2 and 1 to 0·5 per cent of CO; blackdamp from the oxidation of timber has a higher proportion of CO_2, up to 20 per cent; and blackdamp from the oxidation of pyrites may have up to 15 per cent of CO_2 due to the action of the sulphuric acid formed (see page 21) on the white flakings (coal *ankerites*) present. These white flakings consist of carbonates of calcium and iron ($CaCO_3 + FeCO_3$).

The gases given off from the strata as blowers of firedamp, etc., often contain a proportion of CO_2, and this affects the composition of the blackdamp produced by a mine. Nevertheless, when a mine has passed the early stages of development, the composition of the blackdamp, as found from analyses of the return air, is fairly constant, unless special conditions arise, e.g. gob fires. The actual composition of the blackdamp is found as follows: Suppose an analysis of the return air of a mine gave—

$$\left.\begin{array}{lrl} CO_2 & 0{\cdot}65 & \text{per cent} \\ CH_4 & 1{\cdot}05 & ,, \\ O_2 & 19{\cdot}75 & ,, \\ N_2 & 78{\cdot}55 & ,, \\ \hline & 100{\cdot}00 & \end{array}\right\} \text{by volume}$$

It will be remembered that fresh air contains 0·03 per cent of CO_2 and 20·93 per cent of O_2. Now, the atmosphere is the only source of oxygen in the mine air. Hence, the proportion of fresh air present is $\left(\frac{19 \cdot 75}{20 \cdot 93} \times 100 =\right)$ 94·36 per cent.

The amount of firedamp present is	1·05	,,
Hence, the amount of blackdamp present is	4·59	,,
	100·00	

This blackdamp consists of (0·65 – 0·03 =) 0·62 vols. of CO_2
and (4·59 - 0·62 =) 3·97 ,, N_2
4·59

i.e. $\left(\frac{0 \cdot 62}{4 \cdot 59} \times 100 =\right)$ 13·5 per cent of CO_2
and 86·5 ,, ,, N_2

Blackdamp does not support life or combustion, but is not poisonous in air unless it be present in large amounts (see page 40). As the presence of blackdamp corresponds generally with a reduced oxygen content, flame lamps and candles burn with a yellow, dull flame in mine air containing more than 7 or 8 per cent of blackdamp, and with larger quantities the flame is easily extinguished inadvertently by slight shock. The student is again reminded that as the oxygen in the air decreases, the candle-power of a flame lamp decreases very rapidly, a drop of 1·0 in the percentage of oxygen involving a drop of 30 per cent in the illuminating value of the flame, though the flame may still be large.

Blackdamp is found diluted with the return air of all mines, but it occurs in concentration in old workings, in the gob, in old pit shafts and any other localities where coal, timber, and the like have been subject to oxidation in a more or less stagnant atmosphere. The breathing of men and horses, and the burning of lamps, contribute only a little to the formation

of blackdamp in the mine ; but the action of acid mine waters on carbonates (ankerites) present in the coal, often as white flakings, may give rise to appreciable quantities of carbon dioxide in certain mines.

Again, in many firedamp blowers there is a fair quantity of nitrogen, up to 30 per cent, which on analysis of the mine

FIG. 5. HALDANE'S TUBE AND TAPER

air will appear as nitrogen of blackdamp, whereas its origin is rather different. Marsh gases of the present day often contain up to 35 per cent of nitrogen.

Estimation of Blackdamp in the Mine. This is done accurately by mine air analysis, as indicated above, but approximate figures may be obtained by the use of Haldane's tube and taper (in naked light mines) or by Briggs's lamp (in safety-lamp mines). *Haldane's Tube*[1] is an open tube made

[1] *Methods of Air Analysis*, by Haldane.

of stout glass 7 in. long and 0·75 in. in internal diameter, and with it a thin lighted taper is employed. When the taper burns in the tube—held vertical—the draught it creates tends to blow out the flame, and the nearer the bottom of the tube the flame is placed, the greater is the tendency for it to be blown out. Now, any blackdamp in the air is an additional factor tending to extinguish the flame. If the air is pure (20·93 per cent O_2) the taper will burn even though the flame be placed as low as possible in the tube. If, however, there is only 18·7 per cent O_2 present—indicating $\frac{18 \cdot 7}{20 \cdot 93} \times 100 = 89 \cdot 5$ per cent of fresh air, and therefore 10·5 per cent of blackdamp—the flame will be extinguished even though it be placed as high as possible in the tube. Intermediate percentages have intermediate values, so that the tube may be graduated to read directly the amounts of blackdamp and oxygen in the air. The graduations are not equally spaced.

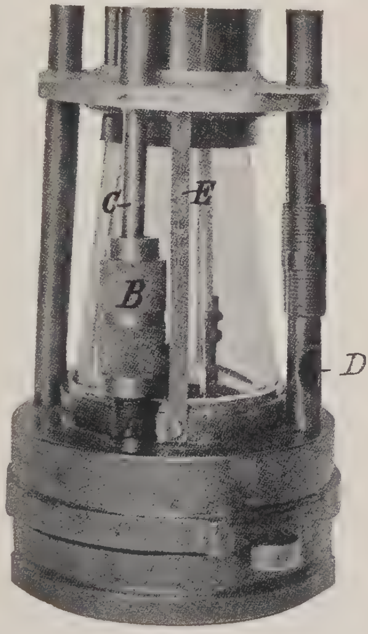


FIG. 6. BRIGGS'S LAMP (OXYMETER)

In *Briggs's Lamp*[1] the air feed to the lamp is through an adjustable aperture *B*, which may be almost closed in pure air without extinguishing the lamp flame. If, however, there is a shortage of oxygen due to the presence of blackdamp, it is necessary to open the aperture more and more if the flame is not to be extinguished. The amounts of oxygen and black-damp present are indicated by the position of the aperture

[1] *Trans. Inst. Min. Eng.*, Vol. LI, page 169.

regulator *B* and may be read off directly. There is also a simple emergency contrivance, *D*, which is normally covered by the thumb when making the tests, by which more air can be immediately admitted to the flame should it threaten to go out. All that is necessary is to remove the thumb. If firedamp is present at the same time as blackdamp, it is necessary to deduct one-fifth of the percentage of firedamp present from the percentage of oxygen indicated ; since fire-damp in small amounts tends to make the flame larger, and therefore to neutralize somewhat the extinguishing effects of blackdamp.

The influence of blackdamp on the limits of inflammability of firedamp in air is discussed on page 54.

Firedamp (Methane), CH_4. Molecular weight, 16. Density ($H = 1$), 8·0. Sp. Gr. (air = 1), 0·56. The gas is also known as marsh-gas, or light-carburetted hydrogen. In the mine it is often referred to simply as " gas." Firedamp blowers are seldom pure methane (CH_4), though methane always forms from 60 to 100 per cent of the gases. Similarly, marsh gases are seldom or never pure methane ; a sample taken recently (1924) from the River Leen at Bulwell, near Nottingham, gave CO_2 3·3 per cent, CH_4 63·5 per cent, N_2 33·2 per cent, H_2S trace. The tendency nowadays, however, is to use the term firedamp for methane pure and simple ; and as the only other inflammable gas which has been found present is ethane, and then only to the extent of 2 or 3 per cent, there is little objection to this usage.

Firedamp (methane) may be prepared by pouring warm water on to aluminium carbide, Al_4C_3.

$$Al_4C_3 + 12H_2O = 3CH_4 + \underset{\substack{\text{aluminium} \\ \text{hydroxide}}}{4Al(OH)_3}$$

The " methane " so produced contains a little hydrogen.

Properties of Firedamp. Methane is a colourless gas without smell or taste. If some firedamps have a faint smell it is due to the presence of traces of impurities, such as H_2S. Methane is only half as heavy as air, and in the mine it is

generally found in greater concentration near the roof, in the lip or ripping face, and in the rise workings. It is an inflammable gas, i.e. burns in air, and when mixed with certain proportions of air it yields mixtures which explode when ignited. It is only slightly soluble in water, 100 volumes of water at 0° C. dissolving $5\frac{1}{2}$ volumes of methane, and at 20° C. $3\frac{1}{2}$ volumes.

The methane of marsh gas is a product of the bacterial decay of cellulose $(C_6H_{10}O_5)_x$, which is the principal constituent of vegetable matter. The firedamp of mines is the marsh gas of the vegetation of which the coal seams themselves have been formed. The gas has been held in the coal and adjoining strata throughout vast ages, probably hundreds of millions of years. Coal is able to absorb methane, especially when the gas is under pressure, and the pressures in some instances must have been enormous. This is shown by the phenomena known as *outbursts of gas* which occur in coal mines from time to time, some seams being more liable than others. An outburst of gas takes place when the gas behind a thin face of coal (or other stratum) is under sufficient pressure to break through with violence. At the same time a quantity of small, almost powdered, coal is ejected, and the atmosphere is rendered explosive, perhaps throughout the mine. Flame lamps become extinguished, but as firedamp has no poisonous action on the human system, other than diluting the oxygen content of the air, even large outbursts of gas do not necessarily involve loss of life.

Detection and Estimation of Firedamp in the Mine. Firedamp in the air in small quantities—up to 4 or 5 per cent—can be detected and estimated by observing the " cap " of burning gas which forms on a flame introduced into such an atmosphere. Normally, the flame is too bright to enable the eye to see the " cap " ; and it is necessary to reduce the flame to a glimmer in order to see the pale blue triangle of burning gas, which is known as the gas-cap. Any flame reduced in this manner till it is practically non-luminous, i.e. any testing flame, will do, but a safety-lamp is generally

used, as there may be more than 5·4 per cent of firedamp (methane) present, in which case an explosion occurs. This is confined to the lamp if a safety-lamp is used.

The following may be taken as the heights of caps given by different percentages of methane, if the lamp flame be about $\frac{3}{8}$ in. broad and $\frac{1}{10}$ in. high, i.e. *almost* extinguished, and practically non-luminous.

TABLE V

Per cent firedamp	Height of cap in inches	Remarks
1·0	0·15–0·20	Most of the cap is visible but its apex is not.
2·0	0·25	Apex of cap just visible.
2·5	0·35	Cap forms an equilateral triangle.
3·0	0·50	Cap is more obvious, and is still visible if flame is raised to a quarter of its full size.
3·5	0·75	Cap still denser.
4·0	1·25	,, ,, ,,
4·5	2·5	,, ,, ,,

The lamp is more likely to pass flame[1] with a small testing flame than with a large, and when testing for gas the fireman first "tries" in the roof, the most likely place, with the flame nearly full-size ($\frac{1}{2}$ in. high). Any large quantity of gas, more than 2·5 per cent, is shown by considerable enlargement of the flame. When testing the main body of the air current, however, in which there is seldom more than 2 per cent of "gas," it is generally necessary to reduce the flame until it is of the size indicated above ($\frac{3}{8}$ in. broad and $\frac{1}{10}$ in. high) and non-luminous.

If a smaller testing flame be used, the caps are smaller than those indicated in the above table; if a larger flame, larger, but not easily visible unless the flame be non-luminous, i.e. unless some special fuel be used, such as alcohol or

[1] To pass flame means to allow flame to pass through the gauze to the outside. This is less likely to occur when the gauze is full of products of combustion than when full of an explosive mixture.

hydrogen. If light oils of the nature of petrol, benzine, colzaline, etc., are employed, the lamp burner is generally small and round, the testing flame consequently small, and the caps small. Nevertheless, the testing flames of these lamps are very sensitive to "gas," as little as 1 per cent being easily observed. Care must be taken, however, not to confuse the gas cap with the normal fuel cap of the flame, i.e. the outer envelope referred to on page 34, in which combustion is being completed. When the lamp and surrounding atmosphere are hot, the fuel cap is greater if light oils are used, due to their volatility. This introduces a little uncertainty into the proportion of gas present, as measured by the size of cap obtained. There are numerous special gas-detecting lamps and devices, but it may be taken as a general rule that the ordinary safety-lamp is the best and soundest indicator. For accurate work gas analysis is necessary.

Requirements of Coal Mines Act. Before we pass to the discussion of the ignition and explosion of firedamp in air, the main provisions of the Coal Mines Act, 1911, dealing with the procedure when gas is found, should be noted: (1) Men must be withdrawn from any place in which the percentage of inflammable gas in the main body of the air exceeds 2·5, and the place must be "fenced off" in all means of ingress. (2) In naked light mines, safety-lamps must be substituted if the percentage of inflammable gas in any place rises to 1·25, or the men must be temporarily withdrawn. (3) Safety-lamps must be used instead of naked lights in any seam where the return air from any ventilating district contains normally more than 0·5 per cent of "gas." (4) All electric machinery must be switched off, if there is present more than 1·25 per cent of "gas" in the air.

The Combustion of Methane. When methane burns in oxygen or air, 1 volume of methane unites with 2 volumes of oxygen and forms 1 volume of carbon dioxide and 2 volumes of steam. The steam, however, soon condenses to water and occupies a negligible volume, so that the original 3 volumes (1 of methane and 2 of oxygen) become 1 volume of

carbon dioxide. The same reactions occur in a methane explosion.

In oxygen $CH_4 + 2O_2 = CO_2 + 2H_2O$

In air $CH_4 + 2O_2 + 8N_2 = CO_2 + 2H_2O + 8N_2$.

The equation for the combustion of methane in air is only approximate, the inert gas being more correctly $(2 \times \frac{79}{21})$ volumes instead of 8; nevertheless, it indicates that the afterdamp from a pure methane explosion consists of CO_2 and N_2, and that 1 volume of methane requires roughly 10 volumes of air to burn it completely. If excess of air be present, the excess is unaffected, and 19 volumes of air to 1 of methane will prevent an explosion. If there is a shortage of air, i.e. less than 10 cub. ft. for each cubic foot of methane, the combustion or explosion will be incomplete, and some CO (carbon monoxide) will be formed as well as CO_2. Most after-damps contain CO (up to 3 or 4 per cent), but the source of such CO is probably an "incomplete" coal-dust explosion, unless the mine be thoroughly wet.

In a mine explosion, there is first an outrush of gases from the source of the explosion, and, secondly, an inrush, or afterblast. The latter is caused, in a pure methane explosion, by the cooling of the hot gases and condensation of the steam produced, thus causing a "partial vacuum." There are other factors also concerned in a coal-dust explosion, but it may be noted here that in consequence of these afterblasts, the coking of coal-dust on the props and bars of the mine roadways is often most marked on the sides *away from* the source.

Table VI, page 53, gives the effect of proportions of gas on a flame. For percentages lower than 5, see Table V, page 50.

It will be seen that the explosive range for methane lies between 5 and 15 per cent, and that the most violently explosive mixture contains about 9·5 per cent of methane and 90·5 per cent of air. This mixture, however, is not as readily ignited as mixtures containing 7–8 per cent of methane, which seem to be the most sensitive, though the exact values depend on the mode of ignition (see page 65). The values for the

TABLE VI

EFFECT OF A FLAME IN MIXTURES OF METHANE AND AIR

% CH_4	Effect
5·0	If the flame be lowered till non-luminous, a long spiral cap several inches tall is visible.
5·4	The flame passes throughout the mixture, even though the source of heat be immediately removed after starting the ignition. This is known as the " Lower Limit of Inflammability."
7·0	More rapid inflammation.
9·5	Most rapid inflammation.
12·0	Less rapid inflammation.
15·0	The flame ceases to pass of its own accord throughout the mixture. This is known as the " Upper Limit of Inflammability.
20·0	The flame is almost extinguished.
25·0	The flame is extinguished.

" lower " and " upper " limits of inflammability also vary somewhat with the mode of ignition ; for instance, whether the mixture be lit at the top or at the bottom of the containing vessel. The following are **Dr. Wheeler's** values obtained at the Eskmeals Experimental Station, the mixtures being contained in a long glass tube 2 in. diameter and fired by an electric spark—

TABLE VII

	Limits of inflammability		Remarks
	Lower	Upper	
Tube vertical, ignition at bottom ..	5·3	14·8	
" " " " top ..	6·0	13·4	Narrow disc of flame
Tube horizontal	5·4	14·3	Flame at top of tube only

If the gases are flowing slowly along the tube, a mixture containing just over 5 per cent methane is inflammable ; and, again, if the mixtures are strongly heated externally up to about 700° C., inflammation takes place of its own accord in the hot gases if only 2 or 3 per cent of methane is present.

It has also been found that if the methane-air mixtures are heated to temperatures less than 700° C. before introducing

a flame, the limits of inflammation are altered considerably, the range being widened as may be seen from the following table[1]—

TABLE VIII

Downward propagation temperature ° C.	Limits of inflammability	
	Lower	Upper
15	6·0	13·4
100	5·45	13·5
200	5·05	13·85
400	4·00	14·75
600	3·35	16·40

The influence of blackdamp on the limits of inflammability of firedamp-air mixtures is, according to **Coward** and **Hartwell** (Safety in Mines Research Board Paper, No. 19), mainly to reduce the upper limit. Thus, using blackdamp containing up to 20 per cent of CO_2, they have found the following approximate limits of inflammability for CH_4—

TABLE IX

Per cent blackdamp	Per cent oxygen	Per cent CH_4			
		Lower limit		Upper limit	
		N_2	$N_2 + 20\% \ CO_2$	N_2	$N_2 + 20\% \ CO_2$
0	20·9	5·3	5·3	14·0	14·0
5	19·9	5·4	5·4	13·0	13·0
10	18·8	5·4	5·4	12·0	11·9
15	17·8	5·4	5·4	11·0	10·8
20	16·7	5·4	5·5	10·0	9·8
25	15·7	5·5	5·6	9·0	8·7
30	14·6	5·6	5·7	8·0	7·7
35	13·6	5·7	6·3	6·9	6·2
38·5 [N_2]	12·9	no inflammation		no inflammation	
34 [80% N_2, 20% CO_2]	13·8	no inflammation		no inflammation	

The ranges are the narrower ones when the blackdamp contains 20 per cent CO_2; and the wider ones when the

[1] See Appendix I to paper on "Flame-proof Casings for Electrical Apparatus," by Hay and Statham (*Trans. Inst. Min. Eng.*, Vol. LXVII, page 36).

blackdamp is entirely N_2. It will be noticed that the upper limit falls by 1·0 when the oxygen percentage falls by 1·0, that is when the blackdamp per cent rises by 5·0; the lower limit is practically unaffected.

Whitedamp (Carbon Monoxide), CO. Molecular weight, 28. Density (H = 1), 14. Sp. Gr. (air = 1), 0·967. Whitedamp is the name given in the mine to carbon monoxide, CO. It is found in the products of combustion of matter containing carbon (e.g. coal, wood, firedamp) if there is not enough oxygen present in the atmosphere to enable carbon dioxide alone to be formed. It is also produced when CO_2 is passed through red-hot coke or red-hot charcoal, and may be prepared in this way. CO is also found in the gases produced by heating coal out of contact with air (i.e. by distilling coal, as at gasworks and coke-oven plant), modern town gas containing, as a rule, from 5 to 15 per cent of CO. Finally, when steam is blown on to red-hot coke, a mixture of carbon monoxide and hydrogen is produced, the mixture being known as *blue water gas*, as it burns with a blue flame.

$$\underset{\text{steam}}{H_2O} + \underset{\substack{\text{carbon}\\\text{(red-hot)}}}{C} = \underbrace{CO + H_2}_{\text{blue water gas}}$$

In the mine whitedamp may be expected (1) in the gases from gob fires, produced by the incomplete combustion of the coal, or by its distillation; (2) in the afterdamps from explosions, in which it is produced in a similar manner; (3) in the fumes from certain explosives (e.g. black blasting powder) where, again, the combustion of the carbon present has not been complete; and (4) in small quantities in the gases produced normally by the slow oxidation of coal (see page 44). The return air from many mines contains 0·01 or 0·02 per cent of CO, a harmless quantity.

As stated earlier, the gas may be prepared by passing CO_2 over coke heated to redness in an iron tube.

$$CO_2 + C = 2CO$$

It may be collected over water.

Properties of CO. CO is a colourless, poisonous gas, with

very little taste or smell. It is but slightly soluble in water, 100 volumes of water at 0° C. dissolving 3 volumes of the gas, and at 20° C., 2·3 volumes.

CO does not support combustion, but itself burns with a blue flame, forming CO_2,

$$2CO + O_2 = 2CO_2$$

It forms inflammable (explosive) mixtures with air when between 16·5 and 72·0 per cent of CO is present, these being its lower and upper limits of inflammability. Such quantities, however, are unlikely even in the gob of a mine, as air containing as little as 1 per cent CO produces death in a few moments. Indeed, atmospheres containing more than 0·1 per cent CO are distinctly dangerous and 0·2 per cent will prove fatal if breathed for a few hours, or in less time if a man is working or exerting himself (e.g. walking).

The poisonous action of CO depends upon the affinity of the haemoglobin of the blood for the gas. This affinity is roughly 300 times as great as that of the haemoglobin for oxygen. Consequently, the blood absorbs CO instead of O_2, and the victim dies for lack of O_2. The body of a person poisoned with CO has a pink, healthy-looking tint, which it retains for some time after death—due to the colour of blood saturated with CO.

In the mine, CO is detected by its action on birds or mice, these being normally overcome before a man; however, the person making the test should proceed slowly, or he may not be able to retire, as the gas affects both the head, causing dizziness, and the limbs.

Small quantities of CO, 0·005 to 0·05 per cent, are best measured by means of Graham's apparatus,[1] in which iodine pentoxide is used; but quantities of 0·05 per cent or more may be estimated by using fractional combustion in the Haldane apparatus.[2] Both methods require care and experience in order to obtain reliable results. The use of a

[1] *Journal of Soc. of Chemical Industry*, 1919, Vol. XXXVIII, pages 10–14T.

[2] *Fuel in Science and Practice*, 1925, pages 450–454.

canary or linnet in a cage is recommended when exploring the workings after a mine explosion: a mouse is not so sensitive. The bird will probably fall from its perch and be overcome by 0·15 per cent in a few minutes. Afterdamps may contain up to 3 per cent or more of CO, and it is this which causes most of the deaths in large explosions.

Afterdamp. Afterdamp is the mixture of gases found in the mine immediately after an explosion. Its composition naturally varies with the type and extent of the explosion, but, as already indicated, afterdamps probably contain as a rule about 3 per cent of CO, and are therefore highly poisonous. The remainder of the afterdamp consists of about 80–90 per cent N_2, 5–20 per cent of O_2, small quantities of firedamp, and traces of other gases.

It is probable that over 80 per cent of the deaths in large mine explosions, i.e. explosions in which coal-dust takes part, are due to the CO poisoning of the afterdamps; and it is principally on account of the CO present in the mine after an explosion that special breathing apparatus has to be worn by the rescue teams. It should be noted, however, that CO is not found in the gases (afterdamp) from a pure firedamp explosion in air, unless there were more than 9·5 per cent CH_4 present before explosion, or unless there were insufficient oxygen present in the air to ensure complete combustion. Thus, with only 18 per cent of oxygen in the mine air, the maximum proportion of firedamp which could be exploded without producing CO in the afterdamp would be $\frac{18}{2} = 9$. A figure less than 9 will be obtained if the firedamp is subsequently added to air containing 18 per cent of oxygen, as the oxygen content of the mixture would be reduced; thus, the figure would really become $\frac{9 \cdot 0}{109} \times 100 = 8 \cdot 26$ per cent.

It is perhaps only in wet mines, however, where pure firedamp explosions of any appreciable size take place, as in the drier mines coal-dust is always liable to participate in the explosion, and generally, as we shall see later, to cause far

more havoc. For the present, it should be noted that where coal-dust takes part in the explosion the afterdamp will almost invariably be highly poisonous, due to its CO content, the CO being formed by the incomplete combustion of the dust or the gases distilled from it.

Stinkdamp (Sulphuretted Hydrogen or Hydrogen Sulphide), H_2S. Molecular weight, 34. Density (H = 1), 17. Sp. Gr. (air = 1), 1·18. This gas is given off during the decay of animal or vegetable matter containing sulphur (e.g. the proteids of eggs), the process being due to bacterial action. It is also found in the gases from volcanoes and in the gases given off when coal is distilled or heated out of contact with air. In the latter case, it is among the first gases to come off; H_2S is, therefore, often found along with CO in the gases coming from gob fires. In the mine it is also present in the fumes from certain explosives, and traces are found in certain firedamps.

H_2S is easily prepared in the laboratory by pouring cold dilute sulphuric acid H_2SO_4 on ferrous sulphide, FeS (not FeS_2)

$$FeS + H_2SO_4 = FeSO_4 + H_2S$$

Properties of H_2S. H_2S is a colourless, poisonous gas, with the most repulsive smell of rotten eggs, which really contain H_2S. The gas is fairly soluble in water, 100 volumes of water dissolving at 0° C. about 440 volumes of the gas, and at 20° C. about 290 volumes. Warmer water dissolves less, so that the gas is often collected over warm water. H_2S burns in air with a bluish flame to form sulphur dioxide SO_2 and water (steam).

$$2H_2S + 3O_2 = 2SO_2 + 2H_2O$$

H_2S is *intensely poisonous*, four or five times as poisonous as CO, but as the nose is sensitive to the smallest traces, the gas is by no means as treacherous as CO. Indeed, it is often a useful guide to the presence of danger, as H_2S usually occurs along with CO in the gases from gob fires and certain explosives. If, however, air containing traces of H_2S be breathed for a few minutes, it is possible to become unaware of the

presence of the gas and then be overcome without further warning. Traces of H_2S may be detected by the "tarnishing" of white blotting-paper which has been wetted with a solution of sugar of lead (i.e. lead acetate), and test papers made in this way are sometimes employed in mines to detect the heating-up of the coal in the early stages of a gob fire.

Nitrous Fumes, Chiefly NO_2. These fumes are given off in quantity when certain nitro-glycerine explosives are fired, e.g. gelignite. They are commoner in metal mines than in coal mines, as weaker explosives (permitteds, see page 129) are generally employed in the latter. Nitrous fumes may be prepared in the laboratory by the action of nitric acid on copper. The fumes are reddish-brown in colour, have a sickly but irritating smell, and are dangerously poisonous. The poisonous action is peculiar; the victim first feels ill and coughs violently, then he recovers, but after several hours there is a second illness with more violent coughing and spitting of blood, generally followed by collapse and death in a few hours. Bleeding has been found to give relief. Poisoning by nitrous fumes, however, is easily avoided by using a water spray to dissolve the fumes (they are very soluble), or by allowing a few minutes for the ventilating current to carry them away.

Incidentally, in coal or metal mines, a round of shots should be fired if possible, so that the shot-firer will not have to breathe any of the fumes; as a general rule, he should proceed against the ventilation, but firing each shot on the intake side of it.

Treatment in Cases of Gassing. The general treatment is as follows—

1. Remove the man to fresh air—or supply oxygen if at hand—keep him warm and dry, and do *not* throw cold water over him. Rub the limbs to warm the body by friction. If he is unconscious and the breathing is shallow or doubtful, lay him face downwards, his forehead resting on his arm, pull forward the tongue, and perform artificial respiration by Schaefer's method.

2. When consciousness has been restored, give a stimulant —either hot, strong coffee or a teaspoonful of sal volatile in a cup of water. Do not allow the patient to walk home, as there is often a recurrence of symptoms on exertion. In all cases keep the patient warm with blankets or the like.

If the man has been poisoned by nitrous fumes, give him an emetic when conscious. Common salt dissolved in tepid water makes a good emetic, but the back of the throat may have to be tickled if vomiting is delayed. Vomiting affords considerable relief and may save the patient's life in cases of nitrous fume poisoning. An emetic is *not* given in cases of gassing by CO, H_2S, firedamp or blackdamp. Gassing with firedamp or blackdamp is really gassing due to oxygen shortage. There is no marked poisonous action.

NOTE.—If at hand, oxygen containing about 5 per cent of carbon dioxide should be administered during artificial respiration. (See page 171.)

CHAPTER VI

THE IGNITION OF FIREDAMP

OUR present knowledge of the ignition and explosion of methane in air comes largely from the pioneer work of **Davy** and the more recent researches of **Dixon**, **Wheeler**, and their assistants. The following notes are based upon the work of Dixon and Wheeler, Davy's contribution being mainly concerned with the development of the flame safety-lamp.

Factors Governing Ignition. It has been seen on p. 53 that the ignition of methane-air mixtures depends upon certain conditions. The important factors are: (1) the proportion of methane present, (2) the temperature of the igniting source, (3) the temperature of the mixture, (4) the temperature, conductivity and specific heat of the surroundings, and (5) whether the mixture is at rest or in (slow) motion (see page 53).

When a source of heat is introduced into an inflammable mixture of methane and air, there is a short time interval before actual inflammation occurs. This interval is known as "the lag on ignition," and during it, "pre-flame combustion" is taking place, i.e. actual combination of the methane with oxygen without the appearance of flame. In this short period of time, the heat developed must be more than that lost to the surroundings if actual inflammation is to follow.

When a flame is used to effect the ignition, the lag interval is very small, less than $\frac{1}{10}$ sec., as the temperature in an ordinary flame is well over 1,000° C.; but if a source of heat of less temperature be employed, the lag may extend to several seconds. In a cylindrical quartz[1] vessel of 5·2 cub. in. (81 cub. cm.) capacity in which mixtures of methane and air were heated, the following figures[2], Table X, were

[1] Quartz was employed to reduce the catalytic effects of the hot surface.

[2] Taken from paper by Prof. H. B. Dixon on "The Ignition of Firedamp," *Trans. Inst. Min. Eng.*, Vol. LXVIII, page 486.

obtained at Eskmeals for the lag on ignition at different temperatures—

TABLE X

Per cent methane	700° C.	725° C.	750° C.	775° C.	825° C.	925° C.	1025° C.
	sec.	sec.	sec.	sec.	sec.	sec.	sec.
4	8·2	3·6	2·4	1·4	—	—	—
6	10·0	4·3	2·6	1·5	0·62	0·21	0·07
8	14·0	5·2	3·0	1·6	0·67	0·25	0·08
10	—	6·3	3·5	1·75	0·72	0·26	0·09
12	—	7·9	4·1	1·90	0·77	0·27	0·09

It will be noted that a 4 per cent mixture is more easily inflamed at any given temperature under these conditions than are the richer mixtures, and that the lag for any given mixture is shorter, the hotter the vessel. But the main fact which these experiments demonstrate is that some time of contact is necessary whenever a heated surface is employed to ignite explosive mixtures of firedamp and air. It is known that such explosive mixtures are not easily ignited by a red hot wire or a charcoal fire. This is because the gases are in motion, due to convection, and there is consequently not enough heat given to each layer of the mixture to compensate for its loss of heat to the surroundings and at the same time to raise the temperature to the point when actual inflammation takes place.

It is, then, impossible to state any definite temperature as the true ignition point of methane. Using a certain apparatus in which the methane and air were heated separately before mixing, Professor H. B. Dixon found ignition points varying from 680° C. to 740° C. When oxygen was used instead of air, the range was from 605° C. to 665° C.; but the values vary over greater ranges when different apparatus are used. This variation is due to the effects of the surface nearby. If this surface absorbs heat in the pre-flame period, the effect will be to raise the ignition point, provided that the surface is large enough, or of sufficient conductivity and specific heat to prevent any great rise in its own temperature. On the

other hand, if the heat absorption is concentrated on to a small surface, the temperature may then rise high enough to ignite the mixture and so lower the apparent ignition point.

To avoid these difficulties, Dixon has found the ignition point of methane-air mixtures by adiabatic compression to the ignition point—i.e. to the self-heating point, not to actual inflammation, which occurs, as we have seen, subsequently. The experiments were done in a cylinder fitted with a piston which could be driven in by a falling weight, the piston being arrested and held by catches at any position. It was found that the mixture of methane and air most sensitive to ignition in this way contained about 7·5 per cent of methane, and was fired when the original volume was compressed to $\frac{1}{11 \cdot 5}$ of its size, i.e. when 100 volumes of mixture were compressed to 8·7 volumes, the pressure being then 28 atmospheres, and the calculated temperature 428° C.

Effect of Pressure. This value, it will be noted, is much lower than the values obtained by the first method, which gave roughly 700° C. as the ignition point, and the question naturally arises, "Does the abnormal pressure make any difference?" Dixon[1] has shown that it does. Using a modification of his original apparatus, in which the air and firedamp were heated separately before mixing, and now putting the gases under various pressures, he has found that the ignition points are lower as the pressure increases, and that at 28 atmospheres pressure an ignition point of about 420° C. may be expected. It has also been noted that, when the pressures are reduced to less than atmospheric, the ignition point of methane rises. Increase of pressure, therefore, favours ignition and decrease retards it; but for most practical purposes we may state that the ignition point of methane-air mixtures is about 700° C., and about 420° C. if compressed suddenly.

The practical aspect of these experiments is important.

[1] See Fourth Annual Report (1925) of the Safety in Mines Research Board, published 1926.

It would seem that in the mine firedamp-air mixtures may be ignited by shock waves from blasting explosives simply by the rapid compression without the introduction of flame at all. A sudden compression to one-twentieth of the original volume will ignite practically all inflammable mixtures of firedamp and air. In the "solid" coal and adjoining strata, however, there is no oxygen present (as a gas), so that there is no fear of igniting the firedamp there. It is in the shot-hole itself and the adjoining crevices where *firedamp-air mixtures* collect, and it is these mixtures that may be ignited by the shock waves from the explosive. Fortunately, shock waves in air have but a small range, and soon die away as they leave the source of the disturbance.

Common Sources of Ignition. The common sources of ignition of firedamp are the flames from explosives used in blasting, the flames of defective lamps and naked lights, the flames and red-hot material of gob-fires, the filaments of damaged electric lamps, electric sparks, and the sparks generated by friction of certain very hard rocks. Most rock sparks are harmless[1] including those of pyrites.[2]

With regard to the ignition by flames, it has been found that while a small gas flame requires an exposure of about 7 milliseconds[1] ($= \frac{7}{1000}$ of a second), a duration of $3\frac{1}{2}$ milliseconds suffices with a larger flame; and that with certain (fully oxidized) explosives the firedamp-air mixtures most sensitive to ignition, as judged by the least weight of explosive necessary to fire them, contain about 9·25 per cent CH_4. Mixtures containing less than 9·0 per cent or more than 9·5 per cent CH_4 often require far heavier charges to ignite them. These facts are of importance with regard to the danger of ignition from the flames of explosives used in blasting.

As pointed out on page 63, the ignition of firedamp-air mixtures under such conditions is influenced to some extent by the adiabatic compression of the gases which takes

[1] Safety in Mines Research Board, Paper No. 8, page 14.
[2] Private Communication from Dr. Wheeler, Director of Experimental Work of Safety in Mines Research Board.

place. This, it is suggested,[1] accounts for the fact that a mixture containing less than 9·5 per cent CH_4 proves most susceptible to ignition by the flame of an explosive, mixtures containing about 7·5 per cent CH_4 being the most easily ignited by adiabatic compression alone—i.e. without introducing a flame.

The Influence of the Igniting Source and the Conditions. Different sources of ignition involve different conditions of ignition, each of which has been investigated by the Safety in Mines Research Board.

That the sensitivity of various methane-air mixtures to ignition depends upon the nature of the igniting source will be seen from the following summary by **Coward** and **Wheeler**[2]—

Mixtures of firedamp and air of suitable composition "burst into flame" when a sufficient volume is maintained at a sufficient temperature for a sufficient time. These three factors are dependent on one another. For example, a large volume of highly explosive mixture may be raised to its ignition temperature and yet may not be inflamed if it is cooled again rapidly enough; whilst but a millionth of a second is long enough for an electric spark, of no unusual intensity, to ignite a portion of the same mixture, with the result that flame is propagated throughout its extent. If, however, a source of heat be less intense, an extension of the duration of heating may compensate for this inferior intensity. Thus, a firedamp-air mixture when raised to its ignition temperature may be apparently unaffected during some ten seconds, but at the end of that time it will suddenly inflame. . . .

The question as to which is the most easily ignitible mixture of methane and air can only be answered when the means of ignition are specified, for the answer depends essentially on the nature of the source of ignition. When contact of the gas with the source of heat is of long duration, as when the gas is enclosed in a heated vessel, mixtures which contain between 5 and 6 or 7 per cent of methane are ignitible at the lowest temperatures; and the lag on ignition, however high the temperature of the

[1] Safety in Mines Research Board, Paper No. 24, "The Ignition of Firedamp by Momentary Flames."

[2] Page 23, "The Ignition of Firedamp," Safety in Mines Research Board Paper No. 8.

surface source of heat may be, is shortest with the mixtures containing the smallest proportion of methane.

When mixtures are heated by sudden compression, those which contain about 6½ to 8 per cent of methane ignite at the lowest temperatures. When the source of ignition is a heated wire, all mixtures which inflame are almost equally ignitible, with perhaps a slight tendency towards greater ignitibility at about 5 to 7 per cent of methane. A 10 per cent mixture seems to be the most ignitible by a gas flame of short duration, whilst a 9 per cent mixture is the most ignitible by the flame of some explosives.

When we turn to consider the incendivity of the various means by which ignition may be effected, we find it impossible to make exact comparisons. It may be said, however, that any ordinary sustained flame (such as that of a lamp) will certainly ignite all inflammable firedamp-air mixtures, for the temperature of a flame is sufficiently high, and its volume is sufficiently great, to fulfil amply the conditions necessary for ignition. Heated surfaces are relatively less dangerous than lamp flames unless their temperature is unusually high; and since the extent of surface is the important factor in determining the time during which the gas in the neighbourhood may remain heated, a body possessing large surface is more dangerous than a wire of the same temperature, and a wire is in turn more dangerous than a frictional spark of equal temperature.

Electric Sparks. "Electric Sparks[1] are more dangerous the more rapidly their energy is communicated to the mixture." The less the duration of the spark, the less is the heat required for ignition of the small volume of gas and air next to the spark, since very little of the heat of the spark then passes uselessly. Consequently, while a certain small volume of gas and air requires a definite quantity of heat to ignite it, yet if the heat is supplied slowly much is lost, and a relatively slow spark such as that produced on breaking an inductive circuit has to be of greater energy to cause ignition than the sudden spark of a condenser or the like. It also follows that high-tension sparks are more dangerous than low-tension (inductance) sparks of equal energy.

A mixture of 8·3 per cent firedamp and 91·7 per cent air is the one most easily ignited by electric sparks,[1] and the

[1] "The Electric Ignition of Firedamp," by R. V. Wheeler, Safety in Mines Research Board Paper No. 20.

character of the current, whether continuous or alternating, has but little influence on the incendivity of the sparks produced.

When volatile metals such as cadmium, zinc, and aluminium are used at the spark-gap, ignition of inflammable mixtures takes place with somewhat lower currents than those necessary when less volatile metals are employed, such as tin, copper, nickel, iron and platinum. This is attributed to the fact that the spark itself is of the nature of an arc, the vapour of the metal acting as the conductor; and this probably explains[1] why sparks from fine (point) contacts are more dangerous than sparks from broad, substantial contacts, the tip of the metal in the former breaks becoming intensely hot (due to high-current density) and sometimes fusing. The prolongation of the heating effects by the hot metal points may thus cause ignition when the spark from a break of larger contact areas may not.

In electric signalling in the mine, bare wires are often employed, and the sparks produced at the wires on breaking the circuit would normally be capable of igniting explosive mixtures of firedamp and air. The explosion at Senghenydd Colliery in 1913 is thought to have been *started* in this manner; it subsequently developed into a coal-dust explosion, and caused the loss of 439 lives. The sparks produced at the trembler contacts of the bell or relay are similarly dangerous, but safety can be obtained there by enclosing the mechanism in a flame-proof casing. Also, layers of tinfoil between the wire layers on the bobbins may be used to cause eddy currents to absorb the energy of the break-flash. A similar contrivance, using a copper band, may be employed for the same purpose in magneto exploders (see page 140).

Among the devices employed for obtaining safety on breaking the contact of the bare wires, the simplest is the insertion of a non-inductive resistance as a shunt across the magnet windings of the bell or relay, the resistance being from 10 to

[1] "The Ignition of Firedamp," by Prof. W. M. Thornton (*Colliery Engineering*, September, 1926, page 388).

50 times that of the windings. This device also helps to suppress the inductive spark at the trembler contacts.

When alternating-current bell circuits are used, the damping may be effected by employing high-resistance shunts across the wires, the resistance being brought into operation by a double contact whenever a signal is given. The maximum pressure allowed for signalling in mines is 25 volts, hence the crest value, when alternating-current is used, is 35 volts $25 \times \sqrt{2}$. The lowest recorded pressure at which a man has been killed by electric shock is 80 volts[1] D.C. equal to 56 volts A.C., since shock sensation depends upon the crest value, not the " root mean square " value.

For further details on safe electric signalling in mines, the reader is referred to the Home Office " Report on Electric Signalling with Bare Wires," by R. V. Wheeler and W. M. Thornton, published 1916, H.M. Stationery Office. It may be noted here, however, that with electric sparks there is no simple law[2] connecting the necessary igniting current with the inductance of the circuit. The energy available for spark production is theoretically $\frac{1}{2}LC^2$, where L is the inductance in henries, and C the current in amperes ; but this expression gives values too high when some of the energy is dissipated in other parts of the circuit, and values too low if the normal working voltage of the system is high. The actual energy of the spark in the latter case is helped by the voltage across the contacts, where, in effect, it leaps from zero before break to the full working value after break, and in the process tends to prolong the spark. In extreme cases this may develop into a continuous arc.

[1] *Mining Educator* (Pitman), page 604, Vol. I.
[2] Safety in Mines Research Board Paper No. 20.

CHAPTER VII

FIREDAMP EXPLOSIONS AND THEIR PREVENTION

The Nature of a Firedamp Explosion. The nature of an explosion is governed by the surroundings; for example, whether there is a free outlet or whether there are obstructions, whether the obstructions are numerous and robust, whether the explosion takes place in a round vessel, or in a tube, or gallery, whether the tube be open at one end or at both, or at neither, whether the gases be at rest or in a turbulent condition, and so forth.

It has been stated that there is no ultimate distinction between a rapid inflammation and an explosion. There are, however, different rates of explosion, and two main types may be distinguished: (1) in which the true "explosion wave" is set up; (2) in which it is not. In explosions of methane and air, the explosion wave is not propagated; or, rather, it has not yet been detected with the apparatus and conditions hitherto employed in the laboratory. In explosions of methane and oxygen, however, the explosion wave is undoubtedly propagated, and its rate of travel in mixtures containing from 11 to 50 per cent CH_4 (i.e. 89 to 50 per cent O_2) varies, according to Dixon,[1] from 8,300 ft. per sec. (2,528 metres) to 5,500 ft. per sec. (1,678 metres), the 50/50 mixture giving the most rapid speed.

The Explosion Wave phenomena were originally observed by **Berthelot.** The explosion wave differs from the flame of an ordinary explosion in (1) its great velocity (1 to 4 miles per sec.), (2) the high momentary pressure it exerts, and (3) the speed at which combustion takes place in it, this type of combustion being known as "explosive combustion" or "detonation."

[1] *Trans. Inst. Min. Eng.*, Vol. LXVIII, p. 495.

When a flame is introduced into an inflammable mixture of gases, there is produced immediately a pressure wave due to the sudden expansion caused by the burning of the mixture near the flame. If the rate of burning of this portion of the mixture is sufficient to generate a pressure intense enough to fire the whole mixture, the mass is *detonated* ; in other words, the explosion wave is propagated. If the rate of combustion is not rapid enough to generate such a pressure, the true explosion wave is not set up, and the explosion, which nevertheless takes place, is only of the nature of a rapid inflammation. The explosion of methane and air, as stated above, falls normally into the second category, i.e. rapid inflammations, but when obstructions are placed in the way, the pressure waves originally sent out are partly reflected, turbulence is set up, and the rate of combustion increases considerably. "Explosion wave" velocities, however, have not yet been reached experimentally.

Speed of Explosion Waves. To form some idea of the relative speeds of (1) the true explosion waves, and (2) the flames of rapid inflammations (explosions), it is useful to remember that while the former vary from about 1 to 4 miles per sec., the latter travel sometimes as slowly as 1 to 4 ft. per sec. or 1 to 4 yds. per sec., though velocities as high as 2,000 ft. per sec. have been registered in an obstructed tube. In the mine, brattice cloths, doors, and small restricted airways will doubtless increase the violence of the explosion.

It may be inferred from the above, then, that pure firedamp explosions in air, i.e. explosions in which coal-dust does *not* take part, will not reach the degree of violence associated with explosions in which the true explosion wave is propagated, and it is common experience that firedamp explosions in wet mines are seldom serious.

The main properties of the explosion, or detonation, wave, have already been indicated, but it will be well to conclude this section with **Prof. H. B. Dixon's** summary[1]: "The

[1] *Trans. Inst. Min. Eng.*, Vol. LXVIII, p. 496.

difference between the phase of vibratory explosion and that of the explosion wave (or detonation) is due to a difference in the intensity and rapidity of the wave-front. In both phases there is a forward movement of a mass of burning gas, piling up pressure in front and leaving a region of partial pressure behind it. In the vibratory phase (inflammation), the pressure in front is not sufficient to fire the unburnt gas ahead with great rapidity by adiabatic compression, and consequently, as the pressure behind diminishes, the flame stops and swings back. In the explosion wave the pressure in the wave front fires the unburnt gas in front with great rapidity —maintaining the flame at constant rate—the burning gases following behind the wave-front for a certain distance before they stop and swing back. The explosion wave may thus be regarded as a single intense oscillation traversing the whole mass of the gas ; its velocity depends upon the heat evolved in the combustion, the specific heats of the gases, and the density of the mixture."

Dixon further points out that, according to Jouquet, " the burning gas must be rushing forward with the velocity of a sound wave in the heated medium, and the explosion wave itself is moving forward also with the velocity of a sound wave *in this moving gas*. The explosion wave is therefore travelling with respect to the stationary tube with *twice* the velocity of a sound wave in the heated gas. That the mass of the gas is rushing forward behind the wave-front, and afterwards stops and returns, is easily seen in photographs taken on a film moving at right-angles to the direction of the wave ; and that the wave-front is travelling with the velocity of sound can be shown by sending a sound wave into the gases just behind the wave-front ; the photograph shows the sound wave running almost parallel with, and therefore at the same rate as, the explosion wave itself.

" The starting of the explosion wave is a sudden act ; the flame which up to this moment has been travelling with an increasing speed, now springs forward at a greater and constant velocity, and at the same moment throws back a wave

through the gases burning in the tube behind it. This return wave has been called the wave of retonation.

"The explosion wave differs from the flame of an ordinary explosion, (1) physically in its great and constant velocity, and in the intense momentary pressure it exerts, and (2) chemically, in the rapidity with which the combustion proceeds."

The Prevention of Firedamp Explosions. The prevention of large "gas" explosions underground may be considered under two heads, (1) the prevention of ignition, and (2) prevention of propagation (of flame).

To prevent ignition there are several methods of procedure: (*a*) the enforcement of the Coal Mines Act (1911) Regulations with regard to the procedure when "gas" is found in the mine air (see page 51), (*b*) the use of electric safety-lamps, (*c*) the use of not more than 25 volts pressure for electric signalling, and then with certain precautions (see page 67), (*d*) the enforcement of the Coal Mines Act (1911) Regulations with regard to the use of "Permitted Explosives" for blasting in "gassy" or "dusty" mines (see page 129). In most of the above, the estimation of firedamp by the cap formed on the reduced flame of a miner's safety-lamp is an essential part of the procedure, but in certain instances mine air analysis is necessary—e.g. in carrying out the Coal Mines Act Regulations *re* switching off the electric current to machinery when 1·25 per cent (or more) firedamp is present.

To prevent propagation of the flame of an inflammable mixture of firedamp and air accidentally ignited, the apparatus (e.g. safety-lamps) in which such ignitions are likely to occur are constructed in a special manner. The two most likely sources of ignition of this kind are (*a*) the flame of a lamp, and (*b*) electric sparks from moving contacts in motors, electric bells, and the like.

Davy's researches indicated the way out of the difficulties in case (*a*), and his use of a metal gauze or perforated metal cylinder or similar contrivance to prevent the passage of flame is still followed.

Safety-lamps and their Gauzes. In a flame safety-lamp a

metal gauze prevents the passage of flame from the interior to the exterior, principally by virtue of the conductivity of the metal, the burning gases being cooled to such an extent that flame cannot pass through the gauze apertures. Convection currents and radiation also play their part in the process, otherwise, with firedamp burning in the gauze, the temperature of the metal would soon become high enough to allow the flame to pass.

It has been found by experiments at Eskmeals and elsewhere that the resistance of a gauze to the passage of an explosion flame in the lamp depends upon : (1) the proportion of open area of the gauze, (2) the area of each aperture, and (3) the diameter of the wire. It also depends upon the size of the lamp-glass, as this affects the size of the lamp, and consequently the possible volume of inflammable mixture which the lamp can hold at any instant. As a general rule, the smaller the lamp-glass (i.e. the smaller the lamp) the safer is the lamp, even neglecting the more likely chance of breakage of the larger glass.

Assuming a glass not taller than 6 cm. (2·36 in.) be used (lamp-glasses are generally shorter than this), it has been found that two gauzes are safe if the mesh be somewhat wider than that originally recommended by Davy. Davy advised a gauze of 28 meshes to the linear inch, i.e. 784 apertures to the square inch, with a gauze cap on top. The Miners' Safety Lamp Committee, in their Report No. 8, recommended that two gauzes be employed, the mesh being only 20 to the linear inch, but the wire stouter than formerly. The following table, taken from their Report, indicates the differences—

TABLE XI

	S.W.G. (standard wire gauge)	Diameter of wire	Apertures per linear in.	Open area per sq. in.	Horizontal candle-power of Marsaut lamp fitted with 2 gauzes
Former gauze .	28	0·0148	28	0·343	0·50
New gauze .	27	0·0164	20	0·451	0·93

The new gauzes are now permitted and are in use in many lamps. The reason for employing the wider mesh gauze is to obtain a greater candle-power from the lamp ; if a chimney is used inside the (new) gauze, as in the Mueseler types, the gain in candle-power is even more marked.

Some lamps employ perforated metal plates instead of gauzes, generally for the inlet or feed air, gauzes or some special form of chimney being used for the outlet. The resistance of a perforated metal plate to the passage of an explosion flame of given intensity depends upon : (*a*) the size of the holes, (*b*) the thickness of the plate, and (*c*) the number of holes per square inch. As a result of numerous experiments, the Miners' Lamp Committee recommended (Report No. 4) that the diameter of holes should not exceed 0·080 in. ; the plate thickness should be at least $\frac{1}{16}$ in., preferably $\frac{1}{8}$ in. ; and the open area should not be more than 55 per cent, preferably not more than 50 per cent.

Flame-proof Electrical Apparatus. The second type of apparatus employed in the mine in which actual ignition of firedamp may take place but flame propagation is prevented, is the electric motor, and other electrical apparatus in which sparking may occur. Such apparatus cannot be made impermeable to air or gas, and, indeed, there is no necessity to do so ; all that is required for safety is a flame-proof casing. This involves the provision of adequate means for the release of the pressure set up by an explosion inside the casing, without at the same time allowing the passage of flame. The main devices are : (1) *Flange Protection*,[1] in which flanges placed close together but not touching are used, the length of the flanges and their distance apart being such that flame cannot pass through the opening. (2) *Gauze or Perforated-plate Protection*, in which holes in the casing are covered with iron gauze or perforated metal plates, safety being obtained in ways similar to those employed in the miner's flame safety-

[1] See " Flame-proof Electrical Apparatus for Use in Coal Mines," by Statham and Wheeler, Safety in Mines Research Board Paper No. 5 (1924).

lamp. (3) *Labyrinth Protection*, in which tortuous passages are employed connecting the interior of the casing to the outside atmosphere. (4) *Relief Valve Protection*, the valves being normally held closed but opening slightly when pressure is exerted from the inside.

Experiments have shown that any of these devices if properly designed will prove satisfactory, and that a gap of as much as $\frac{3}{64}$ in. between flanges 1 in. broad will not allow the passage of flame, though the flanges in actual use should be spaced more closely for safety unless they are made broader. The experiments have also shown that in a closed vessel the maximum pressure given by explosion of mixtures of methane and air is 105 to 110 lb. per sq. in. when the mixture is at rest before ignition, less than $\frac{1}{10}$ sec. being required for its development. The maximum pressure when the mixture is turbulent (before ignition) is a little greater, namely, 114 lb. per sq. in. In both cases the maximum pressure is given by mixtures containing about 10 per cent of methane, and when the mixture is turbulent, i.e. agitated by fan or other means, the time required for the development of the pressure is reduced to less than half of the time required for mixtures at rest. The explosion vessels employed were bronze spheres of 4 litres (7 pints) and 16 litres (28 pints) capacity, respectively.

Flange Protections. If, therefore, flanges are employed as protection devices against propagation of firedamp-air flames, the protection is easily made adequate by leaving the flanges "rough-machined" instead of "finished," so that they are from 0·001 in. to 0·01 in. apart when the apparatus is assembled. It may be added that coal-dust entering at these flanges may cause faulty electrical contacts but is otherwise no source of danger, as experiments[1] have shown that coal-dust on the flange is not ignited by firedamp explosions inside the casing, and "the effect of any coal-dust in the casing is to reduce the violence of the most explosive mixture of firedamp and air if it takes part in the combustion ; nor does

[1] Safety in Mines Research Board Paper, No. 5, p. 44.

the presence of coal-dust augment the explosion of a weak mixture of firedamp and air beyond the maximum that firedamp and air alone can develop."

Perforated-plate Protection. With regard to the use of perforated plates as a protection it has been found[1] that metal plates of the kind indicated in the following table are safe, the thickness of the metal being from $\frac{1}{8}$ to $\frac{1}{2}$ in.

TABLE XII

Diameter of circular hole in inches	Thickness of plate in inches	Number of holes	Total open area per plate in sq. in.	Maximum pressure developed within the enclosure in lb. per sq. in.
$\frac{4}{64}$	$\frac{1}{8}$	37	0·114	62·0
$\frac{4}{64}$	$\frac{1}{4}$	148	0·454	25·7
$\frac{4}{64}$	$\frac{1}{2}$	329	1·010	nil

On the other hand, if very thin metal plates be used, e.g. perforated sheet brass $\frac{1}{32}$ in. thick, safety cannot be attained unless at least two such perforated plates are used, preferably separated by a distance of about $\frac{3}{16}$ in. Moreover, each such plate must have an area of at least 21 sq. in. (preferably 28 sq. in.) per cub. ft. of enclosed air, in order to afford complete release of pressure from an internal explosion with safety. The type of sheet metal recommended is $\frac{1}{32}$ in. thick, and has 108 rectangular holes per sq. in. arranged in rows; the open area of each hole varies from 0·00295 sq. in. on one side to 0·00207 sq. in. on the other, the difference being due to the stamping process of manufacture. Such a plate has an average open area of 0·224 sq. in. per sq. in. of sheet. The ingress of coal-dust can be prevented, it is stated, by using a sheet of lead-foil 0·005 in. thick as a guard, the lead-foil being protected from damage by a grid of stout wire. An internal explosion would rupture the foil but the flame would not pass through and ignite "gas" outside, and the damage to the foil could soon be made good. Other types of sheet metal which, when

[1] Safety in Mines Research Board Paper, No. 21.

used in duplicate, were found to be safe, are given in Table XIII, the one recommended, DD., being included—

TABLE XIII

Laboratory Reference No.	Number of holes per sq. in.	Area of each hole (in sq. in.)		Open area per sq. in. of sheet (in sq. in.)	Type of perforation
		Obverse	Reverse		
AA	240	0·00092	0·00089	0·213	Circular
BB	342	0·00084	0·00055	0·189	,,
CC	126	0·00194	0·00168	0·212	Rectangular
DD	108	0·00296	0·00207	0·224	,,

The spacing of the perforations of CC. differed from that of DD., the main difference being that in CC. the holes were evenly spaced and "staggered," whereas in DD. there were rows of solid metal between the rows of holes, the latter not being "staggered." The holes in DD. were also longer.

The Action of the Gauze or Perforated Metal Plate. The passage of flame from an explosion inside a vessel provided with apertures, e.g. a perforated plate or gauze, tends to be arrested in two ways: (1) by the conductivity of the metal at the apertures, (2) by the cooling produced by the rapid expansion which takes place in the apertures where the pressure is falling rapidly to atmospheric on the outside. When a gauze is used, the conductivity effects generally predominate, and when a plate with many perforations is used, the case is similar. But if a plate with but a few perforations be employed, or a very small piece of gauze, the cooling effects due to expansion may predominate.

It is unsafe, however, to rely on the expansion cooling effect, as it will vary with the composition of the explosive mixture and consequent rate of explosion inside the enclosure. It is mainly conduction effects which have decided the dimensions of the perforated metal plates specified above.

CHAPTER VIII

COAL-DUST EXPLOSIONS

Explosibility of Coal-dust. It has been seen that the conditions requisite for an explosion are those that permit of very rapid combustion. With combustible gases these conditions are easily fulfilled by mixing the gas with air, or better with oxygen, and then introducing a source of heat, e.g. a flame. The combustion then proceeds so rapidly as to be nearly instantaneous, the phenomenon being known as an explosion. Combustible liquids have to be vaporized and mixed with air or oxygen in order to produce a similar explosion; or they may be sprayed into the air or oxygen, as in the cylinders of internal-combustion engines. Combustible solids have to be pulverized to dust and the dust then raised into suspension, as a cloud in the air, to render them explosive; a source of heat of sufficient intensity and duration must of course be introduced. Coal-dust, flour-dust, starch-dust, sugar-dust, can all be made to give explosive mixtures of the above kind by raising clouds of the dust in air, and the explosions are generally very violent.

The history of the investigations into the explosive nature of coal-dust is full of interest, but there is not space here to deal with it: suffice it to say here that the explosibility of coal-dust was suggested by **Buddle** in 1803, and that among the early investigators were **Faraday** (1844), **Galloway** (1870), **Hall** (1876), and **Atkinson** (1886). More recently the work of **R. V. Wheeler** and his staff at Altofts and Eskmeals has placed beyond doubt the fact that coal-dust when present as a cloud in air can be ignited by flame and give rise to intensely violent explosions, and that the presence of gas (firedamp) in the air is not at all a necessary preliminary condition.

Several years ago attention was drawn to the fact that in wet mines explosions were never attended with the havoc that was produced by explosions in dry mines. This was

attributed by some to the cooling or damping effect of the water on the firedamp explosion flame. Others, however, including Galloway and Atkinson, were of opinion that the difference was due to the fact that in wet mines coal-dust took no part in the explosions, whereas in dry mines it did, and this is now known to be true. The great danger of a firedamp explosion in the mine is that it may create a coal-dust explosion by raising a cloud of dust and igniting it. The coal-dust explosion may then spread throughout the mine, even against

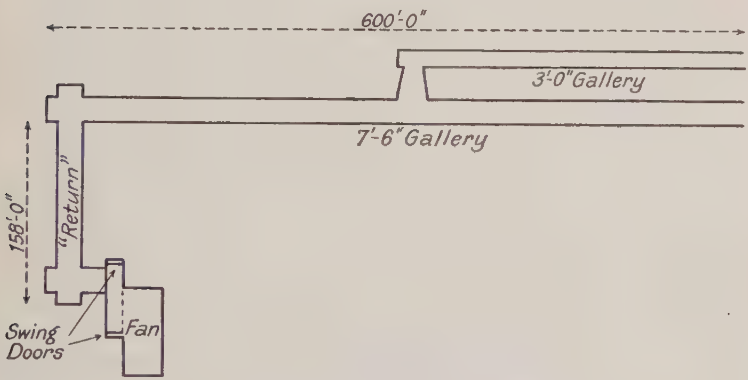


FIG. 7. EXPLOSIONS GALLERY

the ventilating current, continual clouds of dust being raised by the advance pressure waves (pioneer waves), the clouds of dust being subsequently ignited.

Large-scale Experiments. The experiments at Altofts and Eskmeals have been confirmed by the results obtained at similar foreign testing stations, in France, Belgium, Prussia, and the United States. In the English large-scale experiments old boiler shells were utilized to make a gallery 750 ft. long and 7 ft. 6 in. diameter. The gallery consisted of a main straight portion, 600 ft. long, connected through two or three right-angle bends to an exhaust fan. Half-way along the main portion a smaller gallery 3 ft. diameter branched off, as shown in Fig. 7. A valve was fitted near the closed end of the main portion, and in some experiments the closed end was

removed, leaving the main gallery open at both ends. The interior of the gallery was fitted with rails, props, bars, etc., as in a mine roadway ; and, in addition, shelves were used to carry some of the dust. Ignition was effected about half-way along the main gallery by a blown-out shot of gunpowder. The coal used for most of the earlier experiments was an ordinary bituminous coal known as Altofts Silkstone. Analysis of the coal gave the following results—

Proximate analysis		Ultimate analysis (ash-free)	
	Per cent		Per cent
Moisture	4·14	Carbon	80·50
Volatile matter	31·55	Hydrogen	5·45
Fired carbon	62·15	Oxygen	9·70
Ash	2·16	Nitrogen	1·42
		Sulphur	2·93
	100·00		100·00

The coal was ground until 85 per cent of it would pass a sieve of 200 meshes to the linear inch (Institution of Mining and Metallurgy Standard) (see page 94). Experiments have now been done on other coal-dusts, but as it was desired to avoid complications in the earlier stages of the experimental work, only one coal, Altofts Silkstone, was used for most of the work.

The Ignition of Coal-dust. In the Eskmeals experiments the ignition of the dust was generally effected by the shock and flame from a charge of 24 oz. of gunpowder. This was placed in a wrought-iron cannon, 3 ft. long., 6 in. diameter, and bored to a depth of 2 ft. 9 in. with a 2 in. hole for the charge ; it was stemmed tightly with 8 in. of moist clay. The cannon was placed on the floor of the gallery and pointing into an " impetus tube," which consisted of a 10 ft. length of steel tubing 3 ft. diameter, open at both ends and strewn with 20 lb. of coal-dust. More coal-dust was placed on the floor of the gallery at the far end of the " impetus tube," generally for a distance of 12 ft.

It may seem that these conditions are unduly severe, and unlikely in the mine; but they were found desirable in order to *ensure* ignition every time. It must not be thought, however, that they are essential for a coal-dust explosion. **Cadman**,[1] for instance, has shown that coal-dust clouds can be ignited with a candle flame.

The question naturally arises, "When inflammation occurs, does the explosion of coal-dust involve first a distillation of combustible gases from the coal?" The answer is uncertain. It seems probable that in the earliest stages such distillation does occur; but there can be little doubt that in the later stages of the explosion it does not, and that within a second or two after ignition the explosion consists simply in the explosive combustion of the coal particles as a whole.

The Nature of a Coal-dust Explosion. Only the early stages have been examined; the pressures produced in the later stages are too high for the galleries hitherto employed to withstand. When a cloud of dust in a mine roadway or gallery is ignited by a flame, a pressure wave is immediately sent out from the first layers ignited; this is due to the jerking forward of a portion of the air next to the flame, because of the sudden expansion. This pressure wave, or "pioneer" wave as it is called, raises a cloud of dust from any coal-dust lying on the floor or timbers of the road, and provides fuel for the flame of the explosion which follows. The speed of the flame, however, accelerates, and soon reaches the advance or pioneer wave. What then happens is not known; probably the explosion merely slows down for a while only to break out afresh. Behind the flame, however, there tends to be formed a partial vacuum (due to cooling and condensation), and this causes fluctuations in the pressure wave, setting up turbulence, mixing the air and dust more thoroughly and eventually speeding-up the flame—even though it be retarded momentarily. Obstacles and constrictions in the path of the explosion serve only to increase the violence, probably by causing more turbulence.

[1] *Trans. Inst. Min. Eng.*, Vol. XXXVIII, p. 256.

Pressure Development. Information on the rate of pressure development in the Eskmeals Gallery experiments has been obtained by using a special form of pressure gauge (B.C.D. type, i.e. British Coal-dust manometer[1]), which indicates on a chart the pressure at every instant from the time at which ignition is made. A number of such B.C.D. manometers are used at different points along the gallery ; the graphs drawn by them are then compared. An examination of these graphs reveals a number of facts : (1) A small time (about $\frac{1}{5}$ sec.) is required after actual firing of the explosive charge before any pressure at all is registered. (2) This pressure, first noted, is due to the shock wave sent out (at about 1,100 ft. per sec., i.e. velocity of sound in air at ordinary temperatures) on firing the explosive ; the intensity of this pressure is, of course, less the farther it is measured from the source of ignition. (3) The pressure now falls, but not necessarily to zero. (4) The pressure at about $\frac{4}{5}$ sec. after firing the explosive charge rises rapidly, due to the coal-dust explosion which is now taking place. It requires, also, about $\frac{4}{5}$ sec. for the pressure effects due to the shock waves from the explosive charge to die away. (5) The gauges farthest from the ignition source now show the greater pressures and show them before those nearer the source have indicated their maximum values. This means that " explosive combustion " is first attained at about 100 yds. from the igniting source ; in other words, the explosion first becomes intense about 300 ft. (or rather less) from the blown-out shot, and then the pressure suddenly developed seeks release in both directions along the gallery. Consequently, a pressure wave of decreasing intensity is sent back towards the source of ignition. (6) The time of maximum pressure development is not the time of the passage of flame.

Experiments at Eskmeals in 1923 and subsequently have shown that many coal-dusts are more dangerous than the Silkstone dust, inasmuch as they require more than 50 per cent of stone-dust, i.e. a 1 : 1 mixture, to prevent explosion in

[1] See Appendix II to Safety in Mines Research Board Paper No. 3, Coal-dust Explosions, Eskmeals, 1923, by R. V. Wheeler.

the gallery. Among the more dangerous dusts were the Arley, Ayr Hard, Blackband, Black Vein, and Ten Feet.

With regard to the effects of firedamp on coal-dust explosions, the British Coal-dust Experiments indicated that 4·6 per cent of methane was required to render a 1 : 1 mixture of coal-dust (Silkstone) and stone-dust explosive. (Stone-dust acts as a damping medium on coal-dust explosions, as shown later.) The U.S.A. Bureau of Mines Experiments, however, have shown that every 1 per cent of firedamp in the air necessitates an increase of about 5 per cent in the amount of stone-dust required to ensure safety. (See page 90.)

Common Causes of Coal-dust Explosions. The main sources of ignition of coal-dust clouds in the mine are: (1) the flames (and shocks) from firedamp explosions, (2) the flames (and shocks) from explosives used in blasting, more especially if the shots are "blown out," and (3) the arcing of electric cables in dust-laden atmospheres.

The precautions taken to prevent ignition from these sources are: (1) the prevention of firedamp explosions (see page 72), (2) the utilization of permitted explosives only (see page 129), and then with special precautions (page 142), and (3) the enforcement of the safety devices (e.g. earthing) mentioned in the Coal Mines Act Regulations regarding the use of electricity.

In addition to these precautions, however, attempts are made by stone-dusting and watering, as will be seen later, to render the coal-dust difficult to ignite, so that should there be an igniting source, e.g. a firedamp explosion, the coal-dust will not explode. But there can be little doubt that several of the largest and most disastrous mine explosions have been caused through lack of precautions in blasting, more especially through blasting when "gas" is present in the air.

Quantity of Coal-dust Necessary to Propagate an Explosion. A dense cloud of dust is required to *initiate* a coal-dust explosion; and for all mining purposes we may regard the situation as more dangerous the denser the cloud. In other words, the upper limit of inflammation is a cloud of dust so dense as to be difficult of attainment. To propagate an explosion once

started, however, only a minute quantity of dust is necessary. As little as 0·09 oz. per cub. ft. of air space has been known to propagate an explosion, a quantity so small as to be quite unnoticeable on the floor, timbers, etc., of a mine roadway.

For complete combustion of most coals, the calculated theoretical quantity of air necessary per pound of coal is about 10 lb., or 130 cub. ft. at ordinary temperatures and pressures. Thus, 1 cub. ft. of air will combine with $\frac{1}{130}$ lb. of coal or $\frac{16}{130}$ oz., i.e. about 0·12 oz. of dust. It appears, then, that the lower limit of inflammability is reached when rather less than the theoretical quantity of coal-dust is present, but the limiting conditions are by no means fully determined as yet. For "explosive combustion," 0·12 oz. of dust per cubic foot of air would seem ideal, i.e. about 9 per cent by weight or 0·01 per cent by volume, since coal-dust has a specific gravity of about 1·25, or 1 oz occupies $\frac{1}{1250}$ cub. ft.

The practical upshot of the above, however, is to demonstrate the futility of "cleaning-up" alone as a method of preventing the propagation of an explosion. The removal of large dust deposits on the roads will tend to prevent the formation of the dense clouds usually necessary for initiation of the explosion, and is desirable for other reasons, but the dust remaining after the most thorough cleaning is ample to propagate an explosion once started.

CHAPTER IX

THE EXPLOSIVE NATURE OF COAL-DUST

Rendering Coal-dust Non-explosive. The experiments at Altofts and Eskmeals were started to find means of preventing coal-dust explosions. The main conclusions reached may be summarized in the words of the Fifth Report of the Explosions in Mines Committee, as follows—

1. The behaviour of coal-dust varies with the method of ignition. For example, a large flame of burning gas, unaccompanied by any concussion or violent disturbance of the air, will fail to cause even pure coal-dust to propagate flame for more than a limited distance, when the dust is simply deposited in the path of the flame. In order that a self-propagating inflammation of coal-dust should be produced by such a flame it is necessary that the dust should be in suspension in the air as a fairly dense cloud for a considerable distance. When the flame is accompanied by concussion, as is the case with a blown-out shot or over-charged shot, or an explosion of firedamp, it is no longer necessary for the coal-dust to be previously in suspension in the air; but it must be so disposed in the region of the shot that the flame therefrom shall have every chance of igniting a considerable volume of dust-cloud raised by the concussion. In other words, the coal-dust must be thickly in the air before it can be fired.

Cannon-shot Disturbance

2. A mixture in equal proportions of coal and incombustible dust, lying close to the path of the discharge, did not give rise to a spreading inflammation when a charge of 24 oz. of blasting powder was fired from a cannon in the gallery. It is therefore very unlikely that such a mixture lying on the floor or other surfaces of a mine would give a spreading inflammation when subjected to the flame of a blown-out shot from a similar charge.

A mixture in these proportions (1 : 1) is, however, capable of being raised and ignited by a pure coal-dust inflammation (started by means of a cannon shot), and the inflammation so started may then be propagated through the mixture.

Under the same conditions a mixture containing two parts by weight of incombustible dust to one of coal-dust is capable of

prolonging the flame of an inflammation started by a gunpowder shot in pure coal-dust, and the flame may continue for a considerable distance through such mixture before it dies out. Possibly such a mixture might propagate flame indefinitely if the zone of combustion were under still higher pressure. Our experiments have only dealt as yet with inflammations in the clear gallery open at one end and without artificial constrictions.

Travelling Inflammation

3. A slowly-travelling inflammation, such as is produced when a ready-made dust cloud is ignited by a large jet of gas (unaccompanied by concussion), is at first capable of licking up coal-dust deposited upon the surface of an incombustible dust and propagating itself for some distance until sufficient violence is developed to raise the incombustible dust also; and this raising of the incombustible dust is more readily effected when a lighter or more buoyant dust, such as flue dust or fuller's earth, is employed, both coal and incombustible dust being raised in suspension together, and the flame soon dying down.

4. A cloud of ignited coal-dust may travel a considerable distance along a clear gallery free from coal or other dust.

In many cases also, we found that an ignition caused by the cannon and tube succeeded by 250 ft. of pure coal-dust travelled 500 ft. along a gallery strewn with a 2 : 1, or even a 3 : 1 mixture of incombustible dust and coal-dust—the mixture of incombustible dust and coal being partly blown out of the gallery in front of the flame, and partly burned or mingling with the pure coal-dust driven forward from the inflammation zone of pure coal-dust. When the coal-dust forming the inflammation zone is previously diluted so as to contain 40 per cent of incombustible dust, the inflammation is not propagated through a 2 : 1 mixture strewn in front of it along the gallery, since the mingling of the two mixtures cannot form a combustible cloud for any considerable distance.

Effectiveness of Incombustible Dust

5. Incombustible dust is more effective in preventing the ignition of coal-dust than in checking an inflammation that has started. It should, therefore, be distributed uniformly throughout those galleries of the mine subject to the danger of coal-dust ignition, and if maintained in the proportion of between one and two parts by weight of incombustible dust to one of coal-dust, the chances of such ignition taking place would be very small. Even a small proportion of incombustible dust (20 or 30

per cent by weight) has a marked effect in checking an incipient inflammation.

6. The disposal of incombustible dust in zones or in easily-disturbed masses concentrated in certain positions, leaving proportions of the road untreated, is, we think, not likely to be effective.

7. In the case of mild inflammations, an incombustible dust that is readily raised and floats in the air has been found to be more effective than one which, owing to its shape or density, is less buoyant.

Shale dusts, or even heavier dusts, such as sand, are, however, effective when sufficient violence has been attained to raise them in suspension in the air.

The foregoing conclusions led to the Home Office decision to have all roads in dry and dusty mines sprinkled with stone-dust, so that the dust on the roads contained not more than 50 per cent of combustible matter. In this connection, reference should be made to General Regulations, dated 30th July, 1920, Order No. 1423.

There are at present in use two methods of preventing coal dust ignitions in the mine, (1) watering the dust, (2) treating the mine with stone-dust. The latter is more general than the former, and probably more reliable in practice. Both methods are discussed in the next chapter.

Factors Favouring Ignition of Coal-dust in the Mine. These may be summarized as follows—

1. Large deposits of coal-dust.

2. Large proportion of combustible matter present in the mine dust, i.e. a small amount of inert matter, such as water or stone-dust.

3. A large proportion of volatile matter in the coal-dust.

4. A fine coal-dust rather than a coarse one; and a coarse stone-dust rather than a fine one.

5. Presence of firedamp in the mine air, and the absence of blackdamp. Fresh air is somewhat more dangerous than air containing less oxygen.

Dealing with these items in order: (1) The sources of coal-dust are too well-known to mining men to need full description. They include leakage from tubs, dust blown from tubs (in

rapid haulage), dust from coal cutters and conveyors (especially jigger conveyors), dust caused by blasting, and dust from the surface screens, and from the cages in winding. In the mine roadways the dust on the floor often contains a higher percentage of combustible matter than the dust on the roof timbers and sides, though it is not so fine as the latter. The dust on the bars and ledges of the roadways is, however, in a more dangerous position, as it is more easily disturbed. Hence the necessity for throwing stone-dust to the roof and sides.

(2) With many mine dusts, if there is less than 50 per cent of combustible matter present, the inert matter being moisture and stone-dust, ignition is practically impossible. If water alone is used, i.e. no stone dusting, the dust must be converted into a sludge *throughout*, i.e. 30 per cent moisture throughout, before similar immunity is obtained.

(3) **Volatile matter** is the material (gases and vapours) driven off from a dry dust by heating it to a red-hot temperature (900° C.) out of contact with air, i.e. by distilling the coal. Different coals yield different quantities of volatile matter, as shown in Table XIV—

TABLE XIV.

Type of coal	Yield of volatile matter
Anthracites	About 4 to 10 per cent
Bituminous coals	,, 10 ,, 45 ,,
Cannels	,, 40 ,, 55 ,,
Lignites	,, 45 ,, 55 ,,

As a general rule, to which there are a few exceptions, the more the volatile matter, the more easily is the coal-dust ignited. Thus, anthracite dust is most difficult to ignite, and anthracite mines are consequently free from the stone-dusting regulations.

The residue left after driving off the volatile matter is "coke," which consists of fixed carbon and ash. The volatile matter is, except for any steam present, combustible, but so

is the fixed carbon. Consequently, the combustible matter is made up of the volatiles and the fixed carbon. The fixed carbon, on the other hand, must not be confused with the total carbon present ; the volatiles contain a fair proportion of carbon—generally more than one-quarter of their weight.

(4) **The effects of fineness** or the state of division of the particles have not yet been fully investigated—but there can be little doubt that coal-dusts containing a proportion of very fine particles are more dangerous than coarser dusts, other things being equal. Consequently, those coals which, from their natural friability in the mine, give a fair proportion of very fine particles, will probably prove to be the most easily ignited in cloud-form in air, and will probably yield the most violent explosions. On the other hand, if the fineness be such that " clotting " of the particles takes place, it is possible that the very finest dusts may not eventually prove to be the most explosive.

Similarly, the finer the inert particles, clotting being absent, the less easily will ignition be effected, as their cloud-forming capacity will be greater and their damping action more thoroughly distributed. Probably also, the greater the specific heat of the inert dust, the more effective will it be ; though large-scale experiments have not yet indicated any appreciable variations when stone-dusts of different chemical compositions are employed.

Inert Matter. It may be noted at this stage that inert matter in mine dusts is often *naturally* present to the extent of 30 or 40 per cent or more, being derived from (*a*) the natural ash of the coal, and (*b*) the breaking and eventual pulverizing of the strata adjoining the seam. A large proportion of the mine dust is *fusain*, the soft, black, charcoal-like layers of silky or powdery coal, which are generally about $\frac{1}{16}$ in. thick and easily seen along the bedding planes. Fusain may constitute 2 to 5 per cent of the seam, but may occur in the dust to the extent of 40 per cent, or more, as it is easily the most friable portion of the coal. The dull hard coal (bone coal) is known as *durain*, and the bright coal (softs or brights) as

clarain and *vitrain*, the distinction between the two latter being sometimes difficult to see except under the microscope.

It follows from the above that the coal-dust formed by grinding lump coal in a machine may not correspond in its explosive (and other) properties with the mine dust formed naturally ; and that even allowing for the spilling of lump coal in the roadways, and its subsequent pulverizing by traffic, mine dust is likely to be richer in fusain than the prepared dust. Also, it will generally have suffered oxidation to a greater extent. The full effects of these variations have yet to be examined, but it is probable that the prepared dust is more inflammable than " natural " mine dust.

(5) **The presence of firedamp** in the air according to the U.S.A. Bureau of Mines, necessitates about a 5 per cent increase in the quantity of stone-dust used for each 1 per cent of CH_4 present. The British experiments will probably confirm this. With regard to the composition of the air, decreasing the oxygen content reduces the ease of ignition, but it has been found necessary to reduce the oxygen to—

(*a*) 13 per cent before methane is rendered non-explosive ;

(*b*) 18 per cent before coal-dust (Silkstone) is rendered non-explosive ;

(*c*) 16 per cent before coal-dust (Silkstone) is rendered non-explosive, if there is present at the same time 2 per cent of methane.

For rendering coal-dust non-explosive, then, this measure is none too reliable, and is, apparently, unpracticable, in view of the large quantities of air circulating in modern mines, 300,000 cub. ft. per min. or more. Reducing the oxygen content to, say, 16 or 17 per cent, would extinguish all flame-lamps, but would probably have no adverse effects on respiration, unless 3 per cent of CO_2 were present. Increasing the oxygen content of the air would probably render ignition easier, but there are in the mine no sources of oxygen, and the mine air therefore never contains more than 20·93 per cent O_2 (the proportion present in fresh air), but always somewhat less.

CHAPTER X

THE TREATMENT OF MINE DUST

Legal Requirements. The main requirements of the existing Regulations are—

1. Either the mine dust must be sprayed with water so that it contains at least 30 per cent of water in thorough admixture ; or, the mine dust must be stone-dusted until the combustible content in the treated dust is less than 50 per cent ; or some other approved method of rendering the coal-dust less liable to explosion must be adopted.

2. Anthracite mines are exempted from these requirements owing to the difficulty with which anthracite dust is exploded.

3. The stone-dust must be ground so that at least 50 per cent of it will pass through a sieve of 200 meshes to the linear inch, and it must not be injurious to health.

4. When sampling the mine dust (either before or after stone dusting) all particles which are capable of passing through a sieve of 28 meshes to the linear inch are to be regarded as dust.

5. Samples have to be gathered separately from the floor, from the roof and from the sides, over a length of not less than 50 yds. along the roadway. Each sample is sieved through a 28-mesh gauge, and the dust passing the sieve is sent to the laboratory, where its contents of moisture and of combustible matter are estimated by first drying and then incinerating a weighed quantity. Monthly tests must be made and the results posted at the pit head.

Watering the Mine Dust. Watering the mine dust is perhaps the method which most readily suggests itself as a remedy ; since, if the dust be so wet that it cannot form a cloud, there is no fear of a coal-dust explosion. It might, however, be thought that the presence of a smaller quantity of water than that required to convert the dust into a sludge or paste

might be enough to prevent the initiation and propagation of any coal-dust explosion. This is not true. To obtain immunity it is necessary to have at least 30 per cent (by weight) of water present in *thorough admixture throughout.* Unless a mine is naturally wet, the maintenance of this quantity of water in the dust is a matter of difficulty, due partly to the fact that water does not readily mix with or "wet" coal-dust, but mainly to the continual evaporation which is taking place everywhere, thus necessitating continual treatment. Nevertheless, watering is adopted at some few collieries, where it is generally carried out by means of "sprays," in one form or another. In the U.S.A. attempts have been made to utilize exhaust steam.

Sprays. The sprays may be of different kinds, several systems being in vogue. In some mines, fine jets are placed at the requisite intervals on a pipe line running along the roadway, the water being sprayed more or less continuously as a mist of fine globules. In other mines a length of flexible hose is used, fitted with a spray at one end and with a suitable connecting piece at the other to enable it to be attached to the water supply at regular intervals along the road. In these mines the water spray may be directed to any desired portion of the roof, floor, or sides. At other mines, compressed air is used to spray the water, which need not then be under any head. Also, a travelling water tub has been employed, capable of delivering a jet of water from a nozzle when the tub is in motion. One of the axles of the tub wheels is cranked and the motion obtained is used to work a small pump inside the tub.

Whichever method is adopted, the application of the water must be continual if it is to be effective, as the moving air is causing continuous evaporation, and the quantity of water removed per day may be hundreds of tons (see page 30). Hygroscopic salts, such as calcium chloride, have been found partly useful in preventing the rapid drying-up of the dust immediately after treatment, but the use of such substances is very limited, and in most collieries where they have been tried they have not found favour.

The Disadvantages of Watering are many, so that the system by itself is not widely adopted in Britain. The main objections are—

1. In the first place it is not easy to treat the dust so that it shall contain *in intimate mixture throughout* at least 30 per cent of water, due, as already indicated, partly to the natural difficulty of wetting the dust and partly to the continual evaporation.

2. The effects on the floor, roof, and sides of some mines are highly objectionable. It causes disintegration, weakening of the strata, and lifting of the floor. In certain mines the movements may proceed to such an extent as to render the mine unworkable.

3. A considerable quantity of water is required, and the treatment must be continuous in order to replace the continual losses due to evaporation (see page 30).

4. The mine is rendered unpleasantly slippery and muddy for travelling, and ponies find it difficult to get a foothold when pulling sets.

5. In hot mines the evaporation would be most marked and a hot, moist atmosphere would be produced. This would be indicated on the hygrometer by a high wet-bulb temperature reading say 80° F. or over, in which atmosphere it is impossible for men to work without suffering from heat-stroke, due to the difficulty of perspiring properly and so cooling the body. (See page 22.)

Stone-dusting. This method finds more favour than watering, and is more efficient, as it is not subject to the disadvantages mentioned above. It must always be borne in mind, however, that stone-dusting, or watering, is more effective in preventing the *initiation* of a coal-dust explosion than in extinguishing one which has already developed; and that some mine dusts containing less than 50 per cent, even as little as 30 per cent, of combustible matter may be dangerous.

Materials for Stone-dusting—Degree of Fineness. In the General Regulations, the only qualities stipulated are: (1)

That the dust shall be ground so that 50 per cent of it will pass through a sieve of 200 meshes to the linear inch (the concession permitted is not worth consideration), and (2) that the dust shall not be injurious to the health of the workmen. As all modern grinding mills will produce dust of the above degree of fineness, little further attention need be given to the fineness question, except to note that with regard to sieves two separate meshes are employed, a 200-mesh and a 28-mesh. To test the stone-dust, a 200-mesh is to be used, but when sampling the mine dust a lamp-gauze, or 28-mesh, must be employed. Moreover, it should be noted that unless the diameter of the sieve wire is stated, different sieves of the same number of wires per inch may vary considerably in the thickness of the wires employed, and so give widely different screening results. Thus, the Portland Cement Manufacturers' sieves have the thickness of the wire equal to about half the aperture, whereas the I.M.M. (Institution of Mining and Metallurgy) sieves have the thickness of the wire equal to the width of the aperture. The tendency is to adopt the I.M.M. sieves, which have a finer aperture than the Cement Manufacturers for a given mesh. Differences in the apertures are also observable in badly woven sieves; these should be rejected.

Effect of Dust on Health of Miners. The effect of the dust on the health of the men is important. Certain siliceous rocks when ground to dust yield hard angular particles, which may so affect the lungs as eventually to cause phthisis, i.e. consumption, a disease to which metal miners and quarrymen are often subject. Coal-dust, fortunately, has no such effect on the lungs, but, on the contrary, appears to act as a scavenger, stimulating the lung cells to discharge it. According to **Dr. Haldane,** it is probably the *inertness* of silica dust which is responsible for its serious action on the lungs, whereas more chemically and physically active substances, such as coal-dust and gypsum-dust, stimulate the lung cells to activity and are consequently expelled. Indeed, coal-dust and gypsum-dust have been used in metal mines and quarries in order to

protect the lungs against the harmful effects of siliceous dusts ; and in coal-mines it would probably be safe to use the dusts even from sandstone or ganister (both highly siliceous), due to the abundance of coaly particles in the atmosphere. Such dust is naturally not to be recommended, and any dust which "feels gritty" between the teeth should not be used unless special tests by some authority on the subject indicate that it is safe to employ. A microscopic examination will easily reveal the presence of angular crystalline particles, and chemical analysis of the dust may give deciding results in doubtful cases.

Requisite Properties of Stone-dust. It is important, then, that the stone-dust shall not be of a siliceous nature. Further desirable qualities in the material to be used for stone-dust are : (1) It should be of a light colour, preferably white, so that the illumination underground may be improved, and so that the portions of the roadway which have not been treated may be easily noticed. (2) It should be readily available and easily ground to a powder. (3) Its chemical composition should preferably be such that no great complications are introduced into the laboratory routine testing of the mine dust when treated. (4) It should have a high specific heat and low specific gravity. It need hardly be stated that a high specific heat means that the material is capable of absorbing a large quantity of heat without suffering a great increase in temperature. A low specific gravity is desirable, as such a dust will be raised more readily into a cloud. It will be remembered that the specific gravity of bituminous coal is about 1·25–1·35. The specific gravity of most rocks, whether shales, limestones or sandstones, is about 2·5 to 2·7—approximately twice that of coal.

Materials in Use. The materials commonly used as stone-dusts at collieries are : (1) Shale—also called bind, blaes, and metal ; (2) Fuller's earth and substitutes ; (3) Gypsum ; (4) Carbonate dusts, e.g. Chance's Mud and limestone dusts, such as dolomite dusts, oolitic stone-dust (97 per cent $CaCO_3$), etc.

The special tests for mine dusts treated with gypsum and carbonate stone-dusts will be explained more fully later, but it may at this stage be pointed out that *gypsum* is in many respects an ideal stone-dust. It is light coloured, has a specific gravity as low as 2·3, has a high capacity for heat, is very soft and easily ground to a dust of floury consistency.

Water-softener residues are also very desirable materials for use as stone-dusts, but the additional test for carbonate dusts is required, since these dusts consist largely of carbonates of calcium and magnesium.

It has also been suggested that the *dust from boiler plants using pulverized fuel* might with advantage be used for stone-dusting, provided the material is not too gritty. It is already in a fine state of division and incombustible.

With regard to *colliery shales*, it must be noted that on incineration they generally lose about 10 per cent of their weight, due principally to the expulsion of water of hydration. This water of hydration is not driven off by drying at 212° F., and it is consequently recorded as "combustible matter" (being loss on incineration). The error so introduced is not considered serious, and it is on the side of safety. The incombustible mineral matter present naturally in coal and in coal-dusts has generally a composition similar to that of shales (essentially $Al_2O_3 . 2SiO_2 2H_2O$) so that the ash given on incineration of a dry coal-dust or a dry mine dust which has been stone-dusted with shale-dust is rather less than the inert matter present in the dust. Roughly speaking, ash $\times$ 1·1 = inert mineral matter. This fact was borne in mind by the Explosions in Mines Committee in fixing the 50 per cent limit, which virtually becomes a 45 per cent limit, or thereabouts, for the combustible content. To avoid confusion in this matter it may again be stated that the loss on incineration of the dried dust is, for the purposes of the Regulations, taken as the amount of combustible matter present. That this will necessitate the presence of roughly 55 per cent of inert matter instead of 50 per cent is the intention of the authorities, though it will not show in the results of the routine tests.

Fuller's earth stone-dusts call for little comment. It is unfortunate that Fuller's earth is often confused with some of the Fuller's earth substitutes which are employed. In any case, there will be a small loss on incineration due to the elimination of water of hydration (as with the ignition of shales) and such loss, as before, is not allowed for but is registered as "combustible matter."

Preparation of Stone-Dust

Quantity Required. Assuming that ample supplies of inert material are available, it is sometimes desired to estimate roughly the weight of stone-dust necessary to render the mine dust of a certain length of roadway safe, or rather to reduce the combustible content to some given figure, say 50 per cent. For such work an analysis of a sample of the mine dust is first carried out, the sample being taken in the manner to be described later, from a 50-yd. length of roadway, and the material sieved as usual through a gauze of 28 meshes to the linear inch. Suppose that the results of the analysis are: moisture, 3·0 per cent; combustible matter, 63·0 per cent; ash, 34·0 per cent.

Clearly this dust is to be regarded as dangerous, and we require to know the quantity of stone-dust necessary to reduce the combustible content to 50 per cent. The quantity of stone-dust required depends upon two factors: (1) the quantity of mine dust to be treated, and (2) the combustible content of the untreated dust. The first factor is difficult to estimate. Unfortunately, it is almost impossible to obtain an accurate figure for the quantity of mine dust to be treated, as, in the first place, it is difficult to estimate the quantity of dust actually in position per unit length of the roadway, and, secondly, the rate of deposition of the dust varies with the development of the mine. For instance, it depends whether the road becomes a much used haulage road or whether the output on it decreases. It also depends on the velocity of the air currents and the speed of the haulages, and so forth. Attempts have been made by placing special trays at various intervals and in

various situations along a haulage road to estimate the rate of deposition of coal-dust in one or two mines, but no reliable figures are available for generalization, if indeed it be possible to generalize on such a matter. With regard to the second item, however, namely, the estimation of the combustible content of the dust, no such difficulties exist, and it is a comparatively easy matter to calculate the quantity of stone-dust required per pound of mine dust to reduce the combustible content to 50 per cent. In the above example the combustible content is 63 per cent. To reduce this to 50 per cent it is necessary to add to each lb. of dust a certain quantity q lb. of inert dust, such that

$$\frac{0{\cdot}63}{1 + q} = {\cdot}50$$

$$\text{Whence, } 0{\cdot}63 = {\cdot}50\,(1 + q) = {\cdot}50 + {\cdot}50q$$

$$\therefore \quad {\cdot}63 - {\cdot}50 = {\cdot}50q$$

$$q = \frac{{\cdot}13}{{\cdot}50} = 0{\cdot}26 \text{ lb.}$$

Calculations

In general, if there be c per cent of combustible matter in the mine dust and it is required to reduce it to p per cent, then the quantity q (in pounds) of inert matter to be added to each lb. of the mine dust is given by the expression

$$q = \frac{c - p}{p} \quad . \quad . \quad . \quad . \quad . \quad (1)$$

If, however, the stone-dust yields when tested only about 90 per cent of ash, as is usual where colliery shales (i.e. *bind* or *metal*) are employed, the quantity required will be somewhat greater. It is given by the expression

$$q = \frac{c - p}{p - l} \quad . \quad . \quad . \quad . \quad . \quad (2)$$

where l is the percentage loss on incinerating the stone-dust after drying it.

In other words, l will appear as the percentage of combustible matter in the stone-dust, but it may be, and often is, not combustible matter but chemically-combined water.

EXAMPLE. The mine dust on analysis gives the following results: moisture, 4·0 per cent; combustible matter, 59·5 per cent; ash, 36·5 per cent. The stone-dust loses 8·7 per cent on incineration. Find what quantity of stone-dust must be added to each pound of the mine dust to reduce the combustible content to 50 per cent.

SOLUTION. Using the above symbols—

$$q = \frac{c-p}{p-l} = \frac{59{\cdot}5 - 50}{50 - 8{\cdot}7} = \frac{9{\cdot}5}{41{\cdot}3} = \underline{\underline{0{\cdot}230}}\text{ lb.} \quad \textit{Answer.}$$

If the stone-dust had suffered no loss on ignition, the quantity required would have been $\frac{59{\cdot}5 - 50}{50} = 0{\cdot}19$ lb., an appreciable difference.

CHECK.

1 lb. of the mine dust + 0·230 lb. of stone-dust will give—

$$\left.\begin{array}{lr} \text{Moisture . . .} & 0{\cdot}040 \\ \text{Combustible matter .} & 0{\cdot}595 \\ \text{Ash . . . .} & 0{\cdot}365 \end{array}\right\} \text{From 1 lb. of untreated mine dust.}$$

$$\left.\begin{array}{lrl} \text{“ Combustible matter ”} & 0{\cdot}020 & \left(0{\cdot}230 \times \frac{8{\cdot}7}{100}\right) \\ \text{Ash (+ moisture) .} & 0{\cdot}210 & \left(0{\cdot}230 \times \frac{91{\cdot}3}{100}\right) \end{array}\right\} \text{From 0·208 lb stone-dust}$$

$$\underline{\underline{1{\cdot}230}}$$

$$\text{Per cent combustible} = \frac{{\cdot}595 + {\cdot}020}{1{\cdot}230} \times 100 = 50{\cdot}0 \text{ per cent.}$$

In the above calculations, no allowance need be made for the moisture in the stone-dust. With a stone-dust of the nature of gypsum, which on drying at 270° F. loses about 15·7 per cent of its weight—such loss being counted as moisture—the problem is as follows. The loss on igniting undried gypsum is 20·9 per cent, whereas the loss on ignition after drying is only 5·2 per cent of the weight of the original undried

gypsum. Now it is the loss on incineration of the dried material which is the important value, namely, the 5·2 per cent, and this would be the value of l in the expression,

$$q = \frac{c-p}{p-l}.$$

It is seen, therefore, that the amount of stone-dust required per pound of coal-dust may be evaluated as above, but in practice the best way in which to estimate the total amount required is to compare the roadway in question with other roadways having roughly the same type and thickness of dust deposits, where the quantity of stone-dust required has been found by experience. If necessary, due allowance is then made for the amount of combustible matter present originally in the mine dust of such roadways in comparison with the amount present in the roadway to be treated.

Grinding the Dust

Several forms of grinding mill are on the market, capable of pulverizing ordinary colliery shales (i.e. bind or metal) or limestone or so-called Fuller's earth to a degree of fineness such that at least 50 per cent of it will pass through a sieve of 200 meshes to the linear inch. The principal types in use are: (1) Ball Grinders, (2) Hammer Pulverizers, (3) Pestle-and-mortar Grinders, (4) Disc-and-pin Grinders, and (5) Ordinary Mortar Mills (End Runners).

Ball Grinders. In mills of this kind, the material is fed in at the side in pieces about 2 in. cubes, and is broken to powder by means of steel balls falling from plate to plate as the drum rotates, as indicated in Figs. 8 and 9. The plates are perforated with small holes, and the material passing through is first sieved on a screen having holes $\frac{3}{8}$ in. diameter, and secondly on a fine wire sieve of 60 meshes to the linear inch. The material passing this screen is regarded as dust; the remainder is fed back to the mill and again passes through the above cycle of operations. In some cases the ball mill by itself is not recommended by the makers, as it is more especially adapted for producing a coarse powder, though by

using additional sieves (e.g. the 60-mesh sieve above) it can be made to yield dust of the required degree of fineness. If, however, a tube mill is used in addition, as a finishing machine,

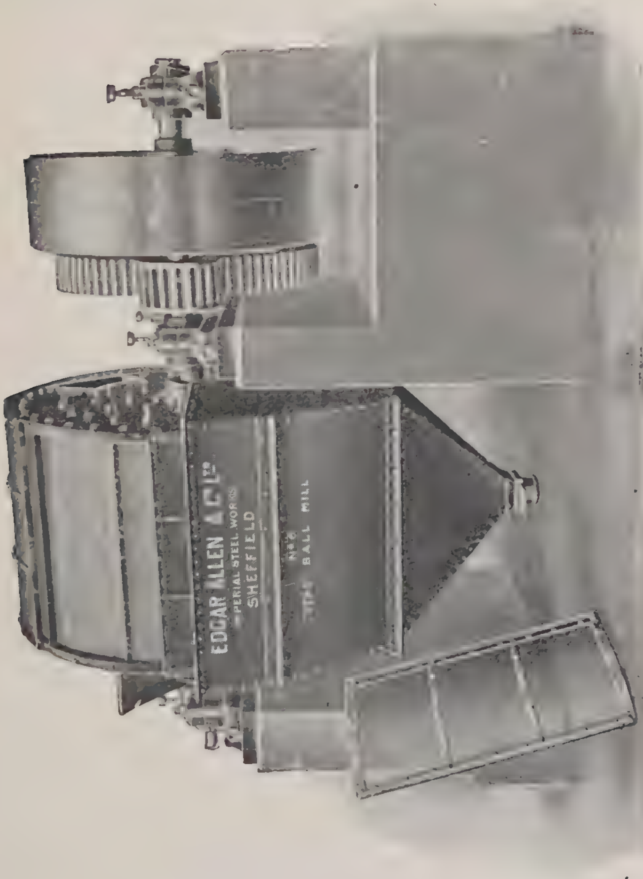


FIG. 8

it is easy to produce a dust of which 50 per cent will pass a sieve of 200 meshes per linear inch.

Tube Mill. A tube mill consists of a revolving tube containing flint pebbles and lined with a suitable silex stone

lining. The flint pebbles perform the grinding as the tube revolves. The feed to the tube mill is by gravity from the ball mill, which in these cases is fitted with a 10- or 20-mesh sieve instead of a 60-mesh, and the fine material delivered by the tube is automatically fed into bags, which have to be

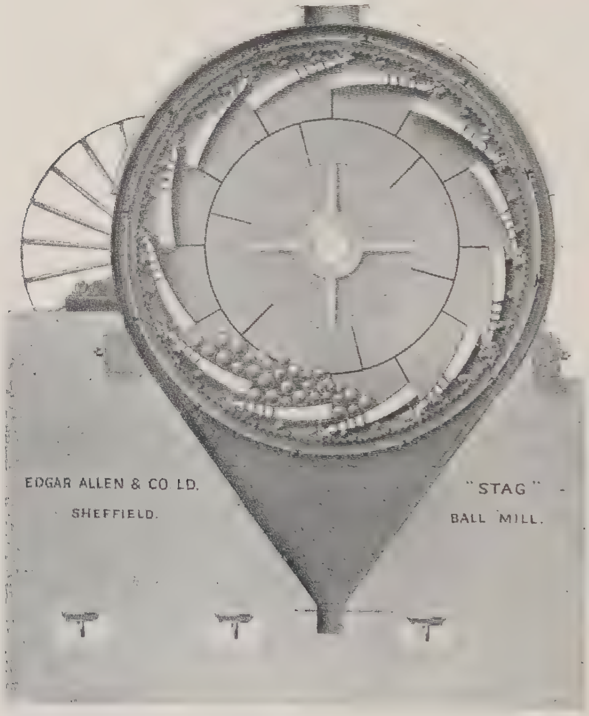


FIG. 9

regularly removed when full. Unless the material is dry before grinding, the sieves tend to become clogged and the tube mill tends to become choked, resulting in reduced output and perhaps complete stoppage; 2 or 3 per cent moisture, however, is not detrimental.

To reduce the shale as sent from the pit to 2- or 3-in. cubes, before feeding to the ball mill, cracking with the hammer may

be employed, or for larger quantities a jaw-crusher may be installed.

A ball and tube mill having an output of about 50 cwt. per hour requires about 45 b.h.p., assuming the feed is of the nature of ordinary colliery shale, roughly, in 2 in. cubes, and

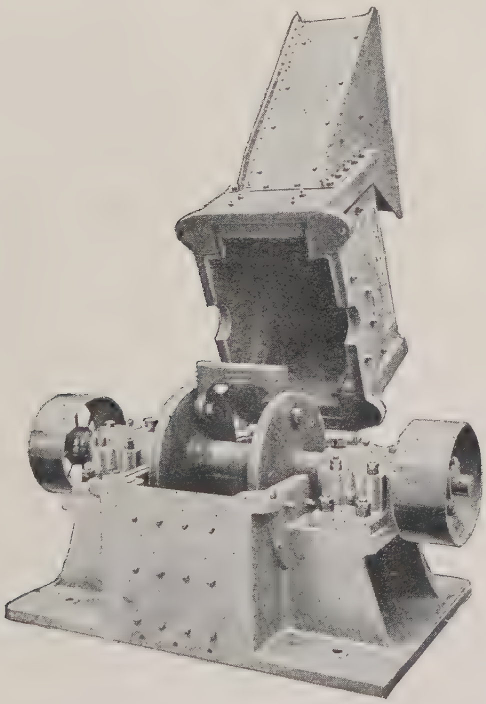


FIG. 10

the delivery is fine dust, of which 50 per cent will pass a 200-mesh sieve.

Hammer Pulverizers. Typical of this class of mill is the Lightning Crusher and Pulverizer illustrated in Fig. 10. It consists of a number of beaters or hammers which are rapidly revolved and strike the material with a number of blows in rapid succession. The dust formed passes through the screen bars indicated.

Pestle-and-mortar Grinders are exemplified in the Griffin Mill made by the Bradley Pulverizing Co. In this mill a pestle in the form of a roller runs inside a mortar in the form of a ring die, and grinds the material to powder in much the same manner as does an ordinary pestle and mortar when used by hand.

A typical Griffin mill installation is indicated in Fig. 11. The material fed to the mill should all pass a $\frac{3}{4}$ in. sieve, and the moisture content should not exceed 2 per cent. This mill yields a very fine dust and requires about 25 h.p. to operate it for an output of about 25 cwt. per hour.

Disc-and-pin Grinders. Typical of these is the Kek grinder. The material in 2-in. cubes, or less, is fed on to the centre of a disc, which is rapidly rotated by a worm wheel driven by pulley and shaft. This disc carries numerous vertical steel pins which almost interlock with similar pins projecting from a second disc fixed rigid and stationary a few inches above the rotating disc. The centrifugal action throws the material outwards, and in passing through the spaces between the moving pins it is ground to a powder or dust, which comes out as a cloud about the level of the discs. This portion of the mill is enclosed in a casing or receiving bin, from the bottom of which the dust is collected in bags.

Ordinary Mortar Mills. The nature of these is familiar to all. They give a coarse dust, however, unless grinding is prolonged, when the yield per hour is necessarily small.

DISTRIBUTION OF STONE-DUST

The distribution of the stone-dust is carried out either by hand or by mechanical means. The dust is sent into the mine in tubs or in bags. If not immediately used, it should be kept in a dry place to avoid the clotting and cementing together of the particles, which frequently occurs in a damp atmosphere. In connection with this matter it should be noted that there is no necessity for having the grinding plant at the surface, and in many mines where electric power is available underground, great advantages will be obtained

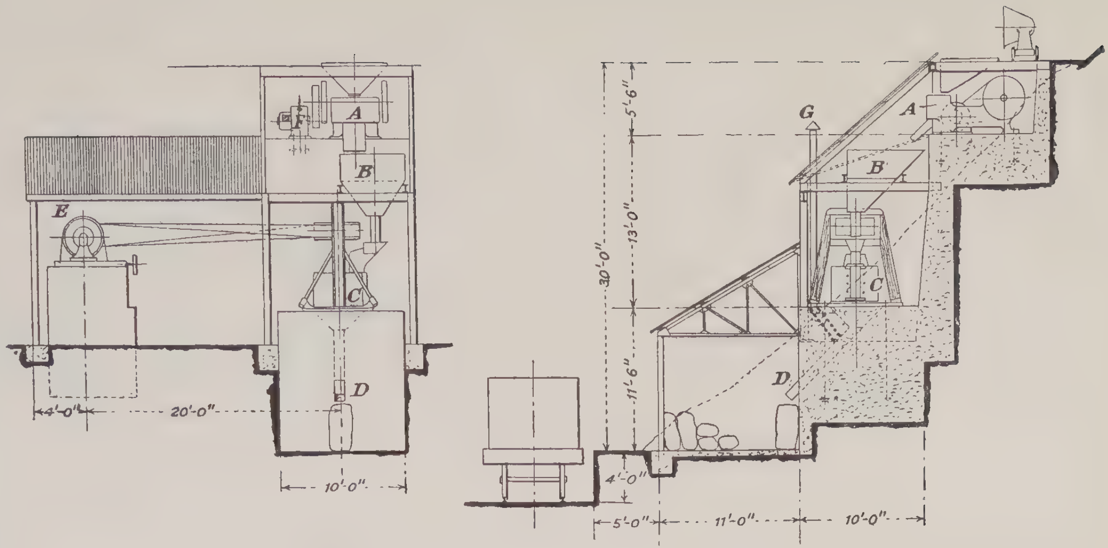


FIG. 11. A TYPICAL GRIFFIN MILL INSTALLATION

A = crusher. B = bin. C = grinding mill. D = discharge. E = driving pulley. F = motor for crusher.

through having the mill near the bottom of the downcast shaft or slightly inbye. There would then be no necessity for winding the shale, the material in dry mines would suffer no risk of becoming moistened, and any fine dust particles escaping as clouds from the grinding plant would be usefully employed in automatically stone-dusting the roads near by. This would result in safer conditions at the bottom of the down-cast shaft—which is frequently a most dangerous place, due to unavoidable deposits of coal-dust—and if the stone-dust were light-coloured a considerable improvement in the illumination would also be effected.

Distribution by Hand. This method is much in vogue and if carried out *thoroughly* by careful and competent persons is perhaps the most efficient. Shovelfuls of the stone-dust are thrown *up to the roof* to dislodge, cover, or intermingle with the coal-dust which has collected naturally on the bars and ledges or other irregularities of the sides and roof of the roadway. The bulk of the stone-dust doubtless falls to the floor, but it is essential that the dust first be thrown upwards in order that as much as possible may lodge on the cross-timbers, etc., and so occupy the most effective positions in the event of an explosion. The method is expensive, however, and unless trustworthy and intelligent men are employed it is not to be recommended.

Distribution by Mechanical Means. Several mechanical devices have been adopted for the purpose of spraying the dust into a cloud. For convenience they may be considered under two heads—

(*a*) Stone-dust sprayers, using a compressed air supply.

(*b*) Travelling-tub stone-dusters, which deliver a cloud of dust as they move along.

The former are exemplified in the Rushton Sprayer and the Hulley Distributor; the latter in the Oldham Stone-duster.

Rushton Sprayer. In this system compressed air pipes are necessary along the roadway underground with connections every 200 yds. or so, where a length of flexible hose may be fitted. The hose at the delivery end is provided with

a **T**-piece made of iron pipes about 2 in. diameter and having an expanding outlet, as indicated in Fig. 12. A nozzle is fitted directly over the vertical limb so that when the latter

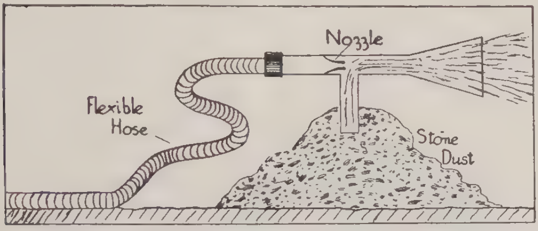


FIG. 12

is placed *loosely* into a pile of the dust, and the air supply turned on, the stone-dust is drawn up the vertical limb and delivered as a dense cloud from the outlet.

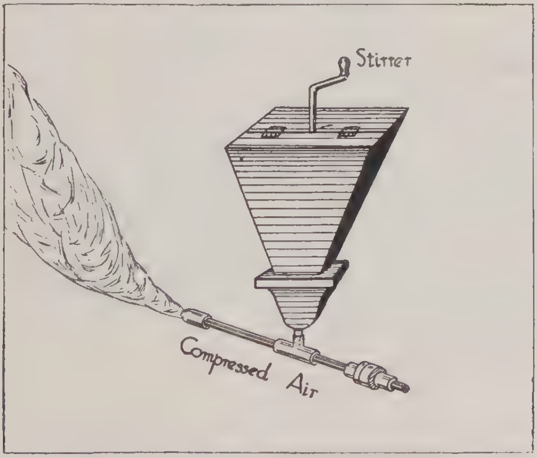


FIG. 13

The stone-dust may be emptied as a pile on the floor, or it may be sprayed directly from the tub.

The Kek Sprayer is similar to the Rushton.

Hulley System. In this case, also, compressed air is required, but as only a small pressure is necessary, a hand-worked air-compressor may be employed instead of attaching

to the compressed air mains. The stone-dust is contained in a hopper having the form of an inverted pyramid. It is provided with a stirring device to ensure a steady supply of dust to the bottom of the box, where a jet of compressed air blows the material into a cloud. See Fig. 13.

Travelling Tub Stone-dusters. The best-known tub of this

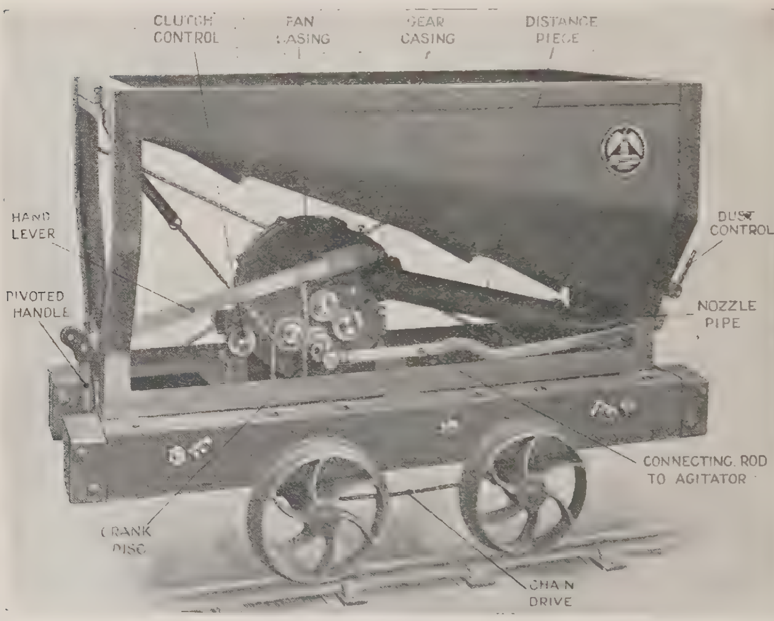


Fig. 14.

class is the Oldham Stone-duster, though other types are in use. Its main features are indicated in Fig. 14. It consists essentially of a tub divided into two halves diagonally, the stone-dust being placed in one and the mechanism, i.e. fan, gearing, levers, etc., in the other. The fan, driven from the tub axles by chains and gearing, creates the necessary draught for blowing the dust into a cloud at the delivery end. The stone-dust is fed in small quantities to the fan outlet by means of a sliding agitator or grid, which travels backwards and

forwards along the sloping floor of the hopper holding the dust. The grid movement is obtained by the connecting-rod indicated.

There is also a lever arrangement by which the fan, etc., can be worked by hand when the tub is stationary, so that stone-dusting can be carried out if necessary at some particular spot without having the tub in motion. Finally, there is a dust-regulating valve by means of which the supply of dust to the fan outlet can be adjusted or cut off entirely if desired. For general purposes along haulage roads there is much to be said for travelling-tub stone-dusters of this type; they should appreciably reduce the cost of the operations, and ensure an adequate and even supply of stone-dust throughout the roadways.

Removing Dust Deposits. Periodically, it becomes necessary to remove the deposits of mine dust. This should *not* be done before stone dusting unless there is very little combustible matter in the natural dust, otherwise dangerous dust is disturbed and transferred from one part of the mine to another as a cloud. Moreover, some of it is transferred from the floor to the roof and sides, which are far more dangerous situations. In clearing up dust deposits, therefore, it is advisable to hang brattices so as to reduce the ventilating current, and, as a general rule, stone-dusting is advisable both before and after the operation.

CHAPTER XI

SAMPLING AND TESTING DUSTS

Sampling the Mine Dust. Accurate sampling is a most difficult operation. It requires time, patience and discrimination to take *representative* samples from a 50-yd. length of roadway, and it is, of course, imperative that the samples taken are representative, if any reliable conclusions are to be drawn. Even using the greatest care, two samplers may take from the same length of roadway samples which when tested in the laboratory will differ in their percentage combustible content by 2 or 3; and the differences obtained if the sampling is carelessly done may easily amount to 10 or 20 per cent, and the whole procedure be thus rendered futile.

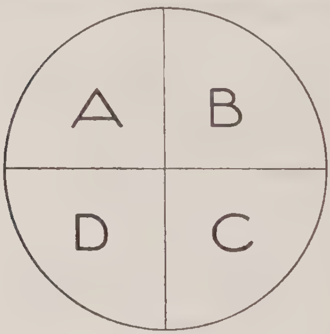


FIG. 15

It is now compulsory to take separate samples from the floor, the roof, and the sides of the roadway. Different conditions in the mine may involve different methods of sampling, but as a guide the following procedure is recommended. At intervals of 5 yds. along the 50-yd. length of roadway gather from the floor by means of a dustpan and handbrush about 1 lb. of the dust, taking portions from places at regular intervals *across* the road. Empty the 9 or 10 samples so obtained on to a clean piece of brattice cloth, and *mix up thoroughly*. From this mixture take a sample by quartering down, i.e. by dividing the heap into quarters, *A*, *B*, *C* and *D* (Fig. 15) and rejecting quarters *A* and *C*. Mix *B* and *D* into a heap and again divide into quarters and reject diagonally opposite quarters. Mix the remaining portions and again

quarter down, and so on until a sample of reasonable bulk, about $\frac{1}{2}$ lb., is obtained. From this, take a handful of dust and sieve it through a 28-mesh gauze into a tin (old "health salts" tins are satisfactory), insert the lid and label the sample properly. Take samples similarly from the roof and from the

FIG. 16

sides. Paper envelopes should not be used instead of the tins unless the dust is apparently dry, as the moisture content may vary in transit. The error so introduced, however, is probably not serious with most mine dusts. If it is preferred to sieve the mine dust in the laboratory, the sieving may be deferred to that stage.

TESTING THE DUSTS IN THE LABORATORY

Mix up the sample thoroughly and take a representative portion of the sieved dust for analysis.

Moisture Test. Weigh a small porcelain or silica crucible or dish and introduce into it about 2 grammes of the dust. Weigh again to get the exact weight of the dust. Place the

FIG. 17

FIG. 18

dish and contents in a water oven for 1 hr. to drive off the moisture. A water oven (Fig. 16) is a copper oven surrounded by a jacket in which water is kept boiling by means of a burner underneath. There may also be arrangements for drawing air through the oven, and a condenser may be used for returning the condensed steam to the water jacket instead of allowing it to escape. The temperature in the oven is thus about 212° F. (100° C.).

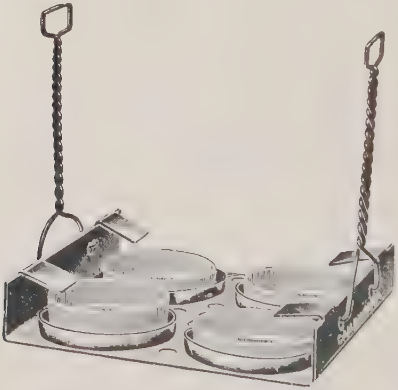


FIG. 19

[A hot-air oven (temp 270° F.) is used for mine dusts which have been treated with gypsum, $CaSO_4 . 2H_2O$, as stone-dust. This temperature is necessary in order to drive off the H_2O of the gypsum; but, even then, only three-quarters of the H_2O

is driven off, i.e. $1\frac{1}{2}$ H_2O.] After 1 hr. allow the dish and contents to cool in a desiccator, i.e. a vessel in which the air is kept dry by some chemical substance, such as strong sulphuric acid, which has a great affinity for water (Fig. 17). It is necessary to use a desiccator because dry coal is very hygroscopic. When cool, weigh again; the loss in weight gives the moisture. The dishes are handled by means of the tongs

FIG. 20

(Fig. 18). A convenient tray for holding dishes is illustrated in Fig. 19. The hooks are detachable.

Combustible Matter—Incineration Test. Now transfer the dish and contents to a red-hot furnace, or place in a bunsen flame, and roast until all combustible matter has burnt away. This may take an hour or more, but the time may be considerably shortened by stirring the material periodically. When all black specks have disappeared, allow to cool and weigh. The loss in weight due to the above incineration gives the "combustible matter content." A suitable electric furnace for carrying out incineration tests is shown in Fig. 20. The

residue in the dish is ash, which is a rough measure of the amount of stone-dust present.

EXAMPLE.

Weight of dish	10·50 grm.
Weight of dish and dust . .	12·50 ,,
∴ Weight of dust taken . .	2·00 ,,

Weight of dish + dust after drying at 212° F.	12·42 grm.
Loss in weight (12·50–12·42 =)	0·08 ,,

$$\therefore \text{Moisture} = \frac{0{\cdot}08}{2{\cdot}00} \times 100 = 4{\cdot}0 \text{ per cent.}$$

Weight of dish + ash (i.e. after incineration) = 11·44 grm.
Loss in weight on incineration (12·42 – 11·44 =) 0·98 grm.

$$\therefore \text{Combustible matter} = \frac{0{\cdot}98}{2{\cdot}00} \times 100 = 49{\cdot}0 \text{ per cent.}$$

Hence, ash = 100 – (4 + 49) = 47·0 per cent.

CHECK.

$$\text{Ash} = \frac{11{\cdot}44 - 10{\cdot}50}{2{\cdot}00} \times 100 = \frac{0{\cdot}94 \times 100}{2} = 47{\cdot}0 \text{ per cent}$$

The above is all that is required by the Coal Mines Act Regulations when testing ordinary mine dusts. In some cases, however, it is desired to know the *volatile* matter content of the dust. This is found as follows—

Volatile Matter Test. Place 1 gramme of the dust in a weighed platinum crucible and weigh again. Cover the crucible with the lid and roast in a full bunsen flame for 7 mins. Allow to cool and weigh again. The loss in weight gives the volatile matter and moisture. It is therefore necessary to deduct the moisture content in order to get the proportion of volatiles The above test drives out of the coal those portions of the combustible matter which give rise to gases or vapours. It does not get rid of all the combustible matter nor even most of it, generally speaking. The bulk of the combustible matter is left as "fixed carbon" in the coke, which remains in the platinum crucible after the above test. To find the amount of fixed carbon, deduct the ash from the coke (see below).

Fixed carbon is not to be confused with the total carbon content. Much of the volatile matter is carbon in various chemical combinations.

EXAMPLE.

Weight of platinum crucible . . .	20·47 grm.
Weight of platinum crucible + dust . .	21·48 ,,
∴ Weight of dust taken . . .	1·01 ,,
Weight after driving off volatiles and moisture	21·28 ,,
Loss in weight (21·48 – 21·28 =) . . .	0·20 ,,

$$\therefore \text{Volatiles} + \text{moisture} = \frac{0{\cdot}20}{1{\cdot}01} \times 100 = 19{\cdot}8 \text{ per cent}$$

But, from the moisture test, moisture . .	= 4·0 ,,
∴ Volatile matter	= 15·8 ,,
Coke = (100 – 19·8)	= 80·2 ,,
Ash (from incineration test) . . .	= 47·0 ,,
∴ Fixed carbon	= 33·2 ,,

CHECK.

Fixed carbon (= total combustible – volatiles)
= (49·0 – 15·8) . . . . . . = 33·2 per cent

TESTING MINE DUSTS CONTAINING CARBONATES

If the mine dust contains carbonates (which happens when a carbonate stone-dust is used, such as chalk, Chance's mud, or water-softener residues) special tests are necessary to find the amount of CO_2 of the carbonates which is driven off on incineration. The chemical equation representing the loss of CO_2 in the case of calcium carbonate, which is almost the only one involved, is—

$$\underset{\text{100 grammes}}{CaCO_3} = \underset{\text{56 grammes}}{CaO} + \underset{\text{44 grammes}}{CO_2}$$

From this it is seen that calcium carbonate on incineration loses nearly half its weight as CO_2, which in the ordinary routine testing of mine dusts would appear as combustible matter, whereas it is useful inert matter. In order to estimate the weight of such CO_2 in a mine dust, a portion of the sample

is treated with dilute hydrochloric acid and the reaction denoted by the following equation takes place—

$$\underset{\text{100 grammes}}{CaCO_3} + 2HCl = CaCl_2 + H_2O + \underset{\text{44 grammes}}{CO_2}$$

The acid clearly removes as much CO_2 as does the incineration. Consequently, the loss in weight is a direct measure of the quantity of such CO_2 in the dust. This is the principle of method 1, given below. In method 2, the volume of the CO_2 given off by the treatment with the acid is measured and the weight calculated, knowing that 1 c.c. of CO_2 at ordinary temperatures and pressures weighs 0·002 gramme.

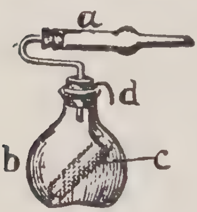


FIG. 21

Method I. Fresenius Method. Place 5 grammes of the mine dust in flask *b*, Fig. 21. Fill the small tube *c* with dilute hydrochloric acid and support it by means of a little cotton thread, *d*, as indicated. Insert the cork carrying tube *a*, which is packed with fragments of calcium chloride to absorb any moisture or spray that may be liberated with and carried along by the CO_2. The whole apparatus is now weighed. Next loosen the thread and allow the acid in *c* to run out and act on the dust in *b*. CO_2 will be given off if any carbonates are present. When all effervescence has ceased, warm the flask gently for a few minutes, and allow to cool, and remove the last traces of CO_2 from *b* and *a* by drawing a slow current of air through. Weigh again. The loss in weight gives the amount of CO_2 present in 5 grammes of the dust. Express this as a percentage value and deduct the value from the percentage combustible as found by incineration.

EXAMPLE.

Weight of mine dust taken	5·00	grm.
Weight of flask and contents (including dust) .	40·52	,,
,, ,, ,, after evolution of CO_2	40·22	,,
Loss in weight	0·30	,,

$$\therefore CO_2 = \frac{0·30}{5·00} \times 100 = 6·0 \text{ per cent.}$$

Assuming the loss on incineration, after drying as usual, were 49·0 per cent, as in the above example, the combustible

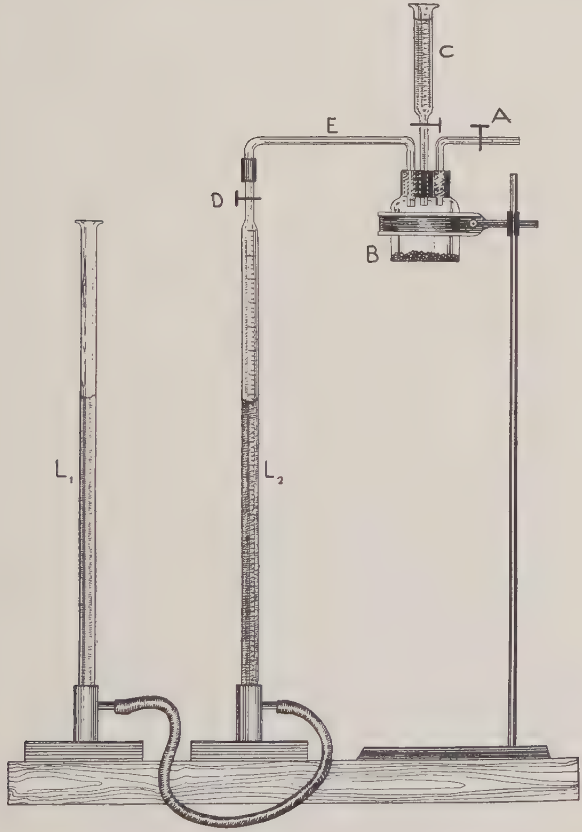


FIG. 22

matter content is 49·0 – 6·0 = 43·0 per cent, and the corrected ash content is 47·0 + 6·0 = 53·0 per cent.

The figures would thus become—

	Moisture	= 4·0	per cent
(corrected)	Combustible matter	= 43·0	,,
(corrected)	Ash	= 53·0	,,

Method II. In this method the *volume* of CO_2 liberated by the acid is measured and the weight calculated.

Transfer 1 grm. of the mine dust by means of a small camel-hair brush into the bottle *B*, Fig. 22. Fill the graduated burette *C* with 14 or 15 c.c. of a dilute solution of hydrochloric acid through which CO_2 has been bubbled for some time so that the solution is unable to dissolve any more of the gas. Half fill the tubes L_1 and L_2 and their rubber connection with a similar solution. Open tap *D* and raise L_1 until the surface of the liquid in L_2 comes to *D*. Close *D* and connect *D* to *E* by the rubber piece indicated. Insert the stopper into *B*, tap *A* being open. Now close *A* and open *D*. The liquid in L_2 will fall a few inches, but should then become steady if there are no leaky connections, and on raising L_1 so that the surfaces of the liquid in L_1 and L_2 are level, the liquid in L_2 should again rise to *D*. In other words, *B* and *E* are full of air at atmospheric pressure. Next run in exactly 10 c.c. of the hydrochloric acid from *C*. CO_2 will be evolved and the liquid surface in L_2 will be depressed. When all action has ceased, level the two liquid surfaces in L_1 and L_2 and read the volume of gas in L_2. Deduct 10 c.c. to allow for the volume of hydrochloric acid added, and the remainder gives the volume of CO_2 liberated. Calculate as follows—

Weight of mine dust taken . . .	1·00 grm.
Volume read on L_2	40·00 c.c.
Volume of acid run into *B* . . .	10·00 c.c.

$$\therefore \quad \text{volume of } CO_2 = 30{\cdot}00 \text{ c.c.}$$

$$1 \text{ c.c. of } CO_2 \text{ at N.T.P.} = 0{\cdot}002 \text{ grm.}$$

$$\therefore \quad \text{weight of } CO_2 = 30{\cdot}0 \times {\cdot}002 = 0{\cdot}06 \text{ grm.}$$

$$\text{and} \quad \text{per cent } CO_2 = \frac{{\cdot}06}{1} \times 100 = 6{\cdot}0$$

As in Method I, this value (6·0) must be deducted from the percentage of combustible matter as found by incineration, and added to the percentage ash. Method II may be carried out more quickly, and, by beginners, more accurately than Method I. As a routine test it is to be preferred.

The Stone-dust Meter. An alternative method[1] of testing mine dusts consists in measuring the "specific volume" of a sample. For full details, the reader may refer to a paper[2] by the author. The principle of the method, however, may be gathered from the following—

Pure coal (bituminous) has a specific gravity of about 1·3, whereas all ordinary rocks, such as shale, sandstone, and limestone, have a specific gravity of about 2·6; in other words 1 c.c. of coal weighs 1·30 grm.

and 1 c.c. of stone weighs 2·60 grm.

It follows that

$$1 \text{ grm. of coal occupies } \frac{1}{1{\cdot}3} \text{ c.c.} = 0{\cdot}77 \text{ c.c.}$$

$$\text{and } 1 \text{ grm. of stone occupies } \frac{1}{2{\cdot}6} \text{ c.c.} = 0{\cdot}385 \text{ c.c.}$$

Or, the specific volume of coal = 0·77, and of shale = 0·385.

Now, if a mixture of equal *volumes* of coal and stone be taken, the specific gravity of the mixture will be $\frac{1{\cdot}3 + 2{\cdot}6}{2}$ = 1·95, whereas if equal *weights* be taken, the specific gravity will be $\left(\frac{2}{\frac{1}{1{\cdot}3} + \frac{1}{2{\cdot}6}} =\right) 1{\cdot}73$. The specific gravity will not be the mean value, since equal *weights* of coal and stone are obviously not equal *volumes*.

On the other hand, a mixture of equal weights of coal and stone will have a specific volume of $\left(\frac{0{\cdot}77 + 0{\cdot}385}{2} =\right) 0{\cdot}577$, i.e. the mean of the values for coal and for stone. Similarly, a mixture of 3 parts by weight of coal and 1 of stone will have a specific volume of

$$\left(\frac{(3 \times 0{\cdot}77) + (1 \times 0{\cdot}385)}{4} =\right) 0{\cdot}673, \text{ or } \frac{0{\cdot}577 + 0{\cdot}77}{2}.$$

[1] This method is not yet officially approved.
[2] *Trans. Inst. Min. Eng.*, 1923, Vol. LXIV, pp. 191–202.

And a mixture of 1 part by weight of coal and 3 of stone will have a specific volume of

$$\left(\frac{(1 \times 0{\cdot}77) + (3 \times {\cdot}385)}{4} = \right) 0{\cdot}481, \text{ or } \frac{0{\cdot}577 + 0{\cdot}385}{2}.$$

Clearly, the specific volume of a mine dust is a linear function of its stone content by weight, and it is, of course, parts by weight which are referred to when we speak of a certain proportion or percentage of stone-dust. [It may be noted in passing that the specific gravity is a linear function of the stone content by volume, but not by weight.]

It is the above principle that is used in the stone-dust meter for the determination of the stone-dust present in a mine dust. The apparatus is simply a device for measuring the volume of a certain weight of the mine dust. The procedure in principle is as follows. Imagine a graduated glass cylinder capable of holding, say, 100 c.c. of liquid. Fill it to the 50 c.c. mark with liquid. Now pour in from a folded piece of paper 25 grm. of mine dust. The level of the liquid will rise by an amount equal to the volume of the dust. Thus, if it were pure coal, the liquid level would rise by $25 \times 0{\cdot}77$ c.c. $= 19{\cdot}2$ c.c., whereas if it were pure stone the level would rise by $25 \times 0{\cdot}385 = 9{\cdot}6$ c.c., i.e. only half as much. Further, if it were half coal and half stone (by weight) the level would rise by $\left(\frac{19{\cdot}2 + 9{\cdot}6}{2} = \right) 14{\cdot}4$ c.c.

In other words, the actual readings on the cylinder would be

$50 + 19{\cdot}2 = 69{\cdot}2$ c.c. for pure coal,

$50 + 14{\cdot}4 = 64{\cdot}4$ c.c. for half coal + half stone,

and $50 + 9{\cdot}6 = 59{\cdot}6$ c.c. for pure stone.

Clearly, if the 69·2 mark be now marked as 0 (zero), and the 59·6 mark be now marked as 100, and the intervening length divided into 100 equal parts, the instrument will read directly the stone content of a dust, provided always that 50 c.c. of liquid are employed and 25 grm. of dust.

The most convenient form of apparatus to use, however, is not a measuring cylinder, but a small flask provided with

a ground glass neck, into which fits an open graduated stem, the capacity of flask bottom + stem to the 100 mark being about 59·6 c.c. The stem is marked 100 near the bottom and zero near the top. The interval is divided into 100 equal parts and is about 8 in. long and ½ in. diameter. The flask should be as "squat" as possible, and the most suitable liquid to employ is methylated spirits, as it readily "wets" the dust. 25 grm. of the mine dust, sieved through a 28-mesh gauze, are placed in the flask, and the graduated stem inserted after vaselining the joint. 25 c.c. of methylated spirits are then run in from a pipette, and the flask held in a cloth, to avoid heating by the hand, and shaken vigorously for two or three minutes to remove all air bubbles; sometimes longer shaking is necessary. The other 25 c.c. is then added and the reading of the level of the liquid in the stem gives at once the stone-dust content. This, as pointed out on page 96, is nearly the same as the "ash" content, and it is not difficult to get good agreement between the stone-dust meter results and the ash results obtained from the usual incineration tests; but differences of 2 or 3 may be found where (1) the sample is not homogeneous, (2) much moisture (6 per cent or more) is present, (3) carbonates (e.g. ankerites, limestone dusts and water-softener residues) are present, (4) gypsum is used as stone-dust. With such dusts it by no means follows that the stone-dust meter

FIG. 23. THE STONE-DUST METER

results are in error as a measure of the mineral (inorganic) matter present; indeed, the errors are more likely in the incineration test, but full consideration need not be given here to the effects of these factors, as they are dealt with in the paper already indicated. One factor, however, may be mentioned as it is of universal importance, namely, the effect of moisture on the results. This is found both in theory and in practice to cause an error in estimating the stone-dust content, the error being equal to one-half of the moisture present. Thus, if the instrument reads correctly for dusts containing, say, 3 per cent of moisture, it will give readings too high for dusts which contain 5 per cent and readings too low for dusts which contain 1 per cent of moisture; and the error for the first dust will be $\frac{5-3}{2} = 1$, and for the second $\frac{3-1}{2} = 1$, i.e. an ash content of 53 per cent, say, will read as 52 per cent for the first dust and 54 per cent for the second.

If possible, it is best to standardize the instrument with mine dusts containing their natural moisture content, i.e. to use samples of natural mine dust and find their ash content (*a*) by incineration and (*b*) by the stone-dust meter, and hence find *exactly* how much liquid to use to make the instrument read truly. This is necessary, as (1) mine dusts differ slightly, (2) the capacity to the 100 mark differs slightly in different instruments, and (3) the 25 c.c. pipettes are not always true. A few trials soon discover whether the volume of spirit should be increased or reduced, but it seldom differs from 50 c.c. by more than 0·2 or 0·3 c.c.

CHAPTER XII

EXPLOSIVES

The Nature of Explosives. An explosive is a substance, solid or liquid, which can be rapidly decomposed into gases by heat or shock. The gases formed tend to occupy a large volume, more especially as they are hot at the time of explosion, and if there is no easy outlet they exert enormous pressures. It is these pressures that are made use of in blasting. Most explosives consist essentially of a combustible portion and a portion which contains oxygen in combination with nitrogen. These two portions may be chemically combined as in *high explosives*, or may be mixed with each other as in *low explosives*, the oxygen and nitrogen portion then being present as a nitrate of a metal, e.g. potassium nitrate, KNO_3. Low explosives, e.g. gunpowder, do not explode rapidly as they are **mixtures** of substances, and the molecules of each substance have to be broken down before combination (oxidation) can take place. Such explosives do not, therefore, set up the true explosion wave. High explosives, on the other hand, explode most rapidly since the atoms, once the explosion has begun, are all ready to recombine; consequently explosives of this class, e.g. nitro-glycerine $C_3H_5(NO_3)_3$, explode with great speed and violence, and so set up the true explosion—or detonation—wave. Gunpowder, the typical low explosive, consists of 75 per cent nitre (KNO_3), 15 per cent charcoal (C), and 10 per cent sulphur (S); the combustible portion consists of charcoal and sulphur, the nitrogen-oxygen portion being in the nitre. In nitro-glycerine, the combustible portion consists of carbon and hydrogen atoms, the necessary oxygen being present combined with nitrogen in the NO_3 groups. The nitrogen in each explosive is more or less inert, but it is an important link for the oxygen atoms, a link just strong enough to hold them together until the vibrations set up by shock or heat cause disruption.

The oxygen atoms then break away, and immediately oxidize any combustible matter present, the rate of combustion being so intense as to be an explosion.

Permitted Explosives are high explosives[1], i.e. explosive compounds, mixed with other substances. These substances include (*a*) oxidizing agents to complete the combustion of any partly burnt gases, (*b*) temperature reducing substances to cool down the hot gases and reduce the flame, and (*c*) mild alkalis to neutralize traces of free acid which might otherwise cause the explosive to decompose on storage. The oxidizing agents used are nitre (KNO_3), barium nitrate $Ba(NO_3)_2$, and potassium chlorate ($KClO_3$). Temperature-reducing substances include common salt ($NaCl$), copper sulphate ($CuSO_4 . 5H_2O$), magnesium sulphate ($MgSO_4 . 7H_2O$), and potassium chloride (KCl). Substances containing water (H_2O) of crystallization are naturally powerful cooling substances: $NaCl$ and KCl, on the other hand, absorb heat simply by their volatilization. The mild alkalis employed are generally either chalk ($CaCO_3$) or magnesium carbonate ($MgCO_3$). Other substances of the nature of woodmeal and flour are incorporated into "permitteds" containing nitro-glycerine, in order to absorb the nitro-glycerine—a liquid. The compositions of certain permitteds are given on page 130, and the tests which such explosives have first to pass are mentioned on page 129.

Low explosives are fired by simple ignition. They do not "detonate," i.e. set up the explosion wave. High explosives, however, and "permitteds," other than bobbinite, require as a rule "detonation" to fire them. **Detonation** consists in firing (by heat or shock) a small charge of sensitive explosive after embedding it in the main explosive charge. The explosion wave set up on firing the detonator rapidly accomplishes the explosion of the main charge, the intense vibrations causing the decomposition of the molecules of the explosive.

Low Explosives. The typical low explosive is gunpowder. The others are essentially gunpowders with modifications in the proportions of the constituents and with certain additions

[1] Bobbinite is the only low explosive on the "permitted" list.

to reduce the flame temperature in bobbinite. The compositions of these low explosives are given in Table XV.

TABLE XV

	British gunpowder	Black blasting powder (variable)	Bobbinite first definition	Bobbinite second definition
Nitre (KNO_3)	75	65	65 – 62	66 – 63
Charcoal (C)	15	15	19·5 – 17	20·5 – 18·5
Sulphur (S)	10	20	2·5 – 1·5	2·5 – 1·5
Ammonium sulphate $(NH_4)_2 SO_4$	nil	nil	17 – 13	nil
Copper sulphate $CuSO_4 . 5H_2O$	nil	nil		nil
Rice or maize starch $C_6H_{10}O_5$	nil	nil	nil	9 – 7
Paraffin wax	nil	nil	nil	3·5 – 2·5
Moisture	1·0 – 2·0	1·0 – 2·0	2·5 – nil	3·0 – nil

In bobbinite (first definition) there must not be more than 11 per cent of ammonium sulphate.

Properties of Gunpowders. The above explosives are black, shiny substances made in pellets of different sizes or into cartridges for different work. One pound (1 lb.) of British gunpowder yields about $4\frac{1}{4}$ cubic feet of gases measured at normal temperature and pressure (N.T.P. = 32° F. and 29·92 in. mercury), but as the temperature of the explosion is high, the actual volume would be considerably greater, perhaps five to ten times as great, assuming atmospheric pressure.

The compositions of the gases (by volume) from gunpowder and from blasting powder are given in Table XVI on page 126.

About half the weight of powder used, however, is left as red-hot or white-hot particles of potassuim carbonate, potassium sulphide and sulphur, and this along with the inflammable nature of the gases produced is the main objection to the use of gunpowder in dusty or "gassy" mines. These objections do not apply to the same extent to the use of bobbinite, as the composition of the explosive is somewhat different. Bobbinite is, therefore, still largely employed for

TABLE XVI

	Gunpowder	Blasting powder
CO_2 per cent	50	32
CO ,, ,, . .	11	34
N_2 ,, ,, . .	33	19
H_2S ,, ,, . .	2·5	7
CH_4 ,, ,, . .	0·2	3
H_2 ,, ,, . .	3·2	5
O_2 ,, ,, . .	0·1	nil
	100·0	100

blasting in coal, as the slow nature of the explosion (of all gunpowders) results in a gradual development of pressure rather than a sudden blow. Consequently, the amount of slack and smalls produced by bobbinite is less than that produced by permitted explosives of the high explosive type, though the latter are undoubtedly less dangerous as sources of ignition of firedamp or coal-dust.

High Explosives. These consist generally of the chemical compounds formed when certain organic substances, such as cotton, glycerine, and toluene, are treated with nitric acid (HNO_3). Sulphuric acid (H_2SO_4) is generally used along with the nitric acid in order to absorb the water produced in the reaction. Thus—

Cotton ($C_{12}H_{20}O_{10}$)

treated with HNO_3 gives $\left\{\begin{array}{l}\text{nitro-cotton}\\ = \text{guncotton}\\ = \text{nitro-cellulose}\end{array}\right\}$ $C_{12}H_{14}O_4(NO_3)_6$

Glycerine $C_3H_5(OH)_3$

treated with HNO_3 gives nitro-glycerine $C_3H_5(NO_3)_3$

Toluene ($C_6H_5 . CH_3$)

treated with HNO_3 gives $\left\{\begin{array}{c}\text{tri-nitro-toluene}\\ = \text{T.N.T.}\end{array}\right\}$ $C_6H_2(NO_2)_3 . CH_3$

Ammonia (NH_3) treated with HNO_3 gives ammonium nitrate NH_4NO_3

Ammonium nitrate contains no carbon in its composition, and is in other respects an exceptional explosive,

Nitro-glycerine is a heavy, oily liquid of specific gravity 1·6. It freezes about 39° F., i.e. 7° F. before water freezes. It is insoluble in water. On complete explosion it yields all gaseous products, as follows, with a certain amount of steam: CO_2 = 63·0 per cent, O_2 = 4·0 per cent, N = 33·0 per cent. The explosion, however, is often incomplete, in which case quantities of nitrous fumes (NO and NO_2) and carbon monoxide (CO) are formed, all highly poisonous gases.

Dynamite. A liquid does not make a "handy" explosive. Nitro-glycerine, therefore, is seldom used raw; more commonly it is absorbed in Kieselguhr, a kind of porous earth, the explosive then being known as dynamite. Dynamite contains up to 75 per cent of nitro-glycerine; it freezes more easily (at 45° F. instead of 39° F.) and is less sensitive to shock. When frozen it has to be "thawed" in order to be detonated completely. The dynamite cartridges are thawed in a pan fitted with a "jacket" into which hot water (160° F.) is poured. If the cartridge be incompletely thawed, some of the dynamite may remain after detonation and be a source of danger.

Gelignite consists of nitro-glycerine with a little guncotton and a variable quantity of sodium nitrate ($NaNO_3$) and woodmeal. Blasting gelatine consists only of nitro-glycerine and guncotton. Average compositions are given in the following table. It should be noted here that *blasting gelatine* and

TABLE XVII

	Dynamite	Blasting gelatine	Gelignite
Nitro-glycerine . .	75	93	63·5
Kieselguhr . . .	25	nil	nil
Nitro-cotton (= guncotton)	nil	7	1·5
Sodium nitrate . .	nil	nil	27·0
Woodmeal . . .	nil	nil	8·0

gelignites, unlike dynamite, are *very sensitive to shock when frozen* (40° F.).

These violent explosives, all containing 60 per cent or more of nitro-glycerine, are not on the permitted list, as they are dangerous in their capacity for igniting firedamp or coal-dust clouds; but they are used extensively in quarrying and sinking, since they are powerful explosives and not adversely affected by water.

Nitro-cotton (guncotton) when mixed with nitro-glycerine gives a gelatinous mass, hence the names gelatine and gelignite.

Tri-nitro-toluene is a yellow crystalline substance not easily exploded except by a detonator. It is much used in high explosive shells, e.g. along with ammonium nitrate to give the explosive known as "amatol," and is now employed in many blasting explosives, including some of the "permitteds."

Ammonium Nitrate is a most important constituent of many explosives, including "permitteds." It is a white crystalline substance which readily absorbs moisture from the air. When heated *gently* ammonium nitrate gives off nitrous oxide, N_2O, i.e. the "gas" of the dentist, the reaction being,

$$NH_4NO_3 = N_2O + 2H_2O.$$

If heated strongly, however, an explosion occurs, the reaction now being

$$2NH_4NO_3 = 2N_2 + 4H_2O + O_2.$$

The liberation of free oxygen is useful, as any CO produced, from the carbon of the organic nitro-substances in admixture, is oxidized to CO_2. Ammonium nitrate is not so violent an explosive as is nitro-glycerine, nor so sensitive. Indeed, it is often not regarded as an explosive, but rather as a useful adjunct, exploding only when the organic nitro-compound, with which it is invariably mixed, begins to explode, as in "amatol," mentioned above. (See also page 130.) Cartridge cases for explosives containing ammonium nitrate have to be made of waterproof material, such as waxed paper or metallic foil, and the explosives must be stored

in a dry place, otherwise the ammonium nitrate, being hygroscopic, soon absorbs moisture from the air in large amount, and the cartridge becomes useless. Ammonium nitrate gives off very little heat on decomposing, and is, therefore, most useful in permitted explosives for "dusty" and "gassy" mines.

Permitted Explosives. In dry and "dusty" mines or mines in which firedamp has been found within the last three months in such a quantity as to be indicative of danger (i.e. in safety-lamp mines), no explosives other than "permitted explosives" may be employed. Before being "permitted," the explosives are subjected to the following test: A charge of the explosive is placed in a small cannon without stemming, and fired in a gallery containing a mixture of 13·4 per cent coal-gas and 86·6 per cent air. The charge is then increased or decreased until the largest charge is found which will not ignite the gas and air mixture. A similar procedure is carried out with coal-dust clouds in the gallery, the safe maximum again being found and verified, in each case, by firing five consecutive shots. Whichever of the above safe maximum charges is the less, is known as the *maximum charge*, and it must not be less than 8 oz. The coal-dust is ground so that at least 90 per cent passes a sieve of 150 meshes to the linear inch. The testing gallery is about 5 ft. in diameter, and 30 ft. long.

There is also a *pendulum test*, in which shots are fired at a ballistic pendulum, the swing of which is registered as a measure of the strength of the explosive. The ballistic pendulum consists of a 5-ton mortar swung by 9 ft. rods from a horizontal shaft supported in nearly frictionless bearings. No appreciable amount of the charge must be left unexploded in the shots of the pendulum test.

In Belgium, France, and the United States, firedamp is used in place of coal-gas in the tests, about 8 per cent CH_4 being generally employed.

Permitteds fall into three main classes: (1) nitro-glycerine type, (2) ammonium nitrate type and (3) mixtures of (1) and (2).

Two examples of each are given below—

(1) Nitro-glycerine Type

Essex powder		Samsonite No. 3	
Ingredients	Parts by weight	Ingredients	Parts by weight
Nitro-glycerine	24 – 22	Nitro-glycerine	52·5 – 50·5
Nitro-cotton	1·5 – 0·5	Nitro-cotton	4 – 2
Nitrate of potassium	35 – 33	Nitrate of sodium	11 – 9
Wheat flour (dried at 100° C.)	7 – 5	Chloride of sodium	11 – 9
Moisture	5 – 2	Borax	26 – 24
		Moisture	1·5 – 0

(2) Ammonium Nitrate Type

Denaby powder		Gathurst powder	
Ingredients	Parts by weight	Ingredients	Parts by weight
Ammonium nitrate	35 – 33	Ammonium nitrate	52 – 49
T.N.T.	14 – 12	T.N.T.	18·5 – 16·5
Potassium nitrate	34·5 – 32·5	Potassium nitrate	7 – 5
Ammonium chloride	20·5 – 18·5	Sodium chloride	26 – 24
Moisture	1·5 – 0	Moisture	2 – 0

Nitro-glycerine Plus Ammonium Nitrate Type

Rex powder		Tees powder	
Ingredients	Parts by weight	Ingredients	Parts by weight
Nitro-glycerine	13 – 11	Nitro-glycerine	11 – 9
Woodmeal	8·5 – 7	Woodmeal	10 – 8
Ammonium nitrate	61 – 58	Ammonium nitrate	61·5 – 58·5
Sodium chloride	20·5 – 18·5	Sodium chloride	21 – 19
Moisture	2·5 – 0	Moisture	2 – 0

It will be remembered that the objections to nitro-glycerine explosives are that the cartridges have to be thawed if the temperature is low (45° F. or less) and that they may on explosion give off some nitrous fumes and CO. The "freezing" trouble, however, has now been largely overcome by adding nitrated polyglycerines to the nitro-glycerine, the explosives then being known as "low freezing" explosives. The main objection to ammonium nitrate explosives is that the cartridge must have a waterproof cover, owing to the hygroscopic nature of ammonium nitrate.

The detonator to be used when firing permitteds is generally a No. 6, but occasionally a No. 7, see page 133.

Detonators. The function of a detonator has already been indicated (page 124). The usual type of detonator consists of a small copper case (aluminium cases are not permitted in "gassy" or "dusty" mines) about 2 in. long and $\frac{1}{4}$ in. diameter, containing at one end a mixture of mercury fulminate and potassium chlorate in the proportions of 4 : 1. Next to this is a priming charge of some easily ignited mixture. Into the priming charge are led two wires if electric firing is employed, which is now common. If, however, fuse is employed to ignite a detonator, the end of the fuse is placed in contact with the priming charge and then held in position by crimping the detonator casing (at the fuse end) with a pair of special pliers.

Detonators fired electrically may be of the low-tension or the high-tension type. In *low-tension* detonators the two wires which are led (through a sealing pad of some waterproof cement) into the priming charge are bridged there by a short fine wire bridge, *d*, Fig. 24. The wire may be of platinum or of constantan or similar alloy. The passage of an electric current heats it to redness and fires the detonator.

In Fig. 24, *a* and *b* are the electric leads, and *c* is the cement pad.

In *high-tension* detonators the bridge wire *d* is not used, and the priming composition is ignited either by the spark which passes across the ends of the wires, these being brought

close together, or more probably by the heat generated by the resistance of the priming charge. Different priming or flashing mixtures are employed in different detonators, whether low-tension or high-tension. One low-tension priming composition contains potassium chlorate ($KClO_3$) and antimony sulphide (Sb_2S_3), which mixture is fused on to the platinum wire bridge before it is inserted in the detonator casing, thus avoiding damage to the wire bridge in the manufacture.

Fig. 24
Low-Tension Detonator

High-tension priming compositions are also various, one being a mixture of collodion (celluloid), graphite, and copper acetylide. The wires are kept apart inside the detonator by means of small cardboard strips.

In the mine the electric current for firing detonators is almost invariably produced by a magneto exploder (page 139), but electric batteries could be directly employed, if permitted, for firing low-tension detonators; and with a suitable coil, high-tension detonators could be fired similarly from a single dry cell.[1]

The standard detonators commonly used in blasting are numbers 6 and 7 of the Table XVIII. The "composition," as already stated, consists of four parts by weight of fulminate of mercury to one part by weight of potassium chlorate.

Caution. Detonators should always be handled with the greatest care; they are easily exploded with slight shock or friction.

Low-tension detonators can be tested for the soundness of the circuit before use by placing the detonator in an iron pipe to avoid accidents and sending through the detonator a very feeble current from a special battery. A galvanometer is included in the circuit, and if there is no deflection of the needle, the detonator is useless and should be destroyed. Firing cables may be tested similarly. High-tension detonators

[1] Safety in Mines Research Board Paper No. 11.

TABLE XVIII
STANDARD DETONATORS

No.	Length (external)		Diameter (external)		Weight of "composition"	
	in mm.	in ins.	in mm.	in ins.	in grams	in grains
5	30 – 32	1·18 – 1·26	6·0	0·236	0·8	12·4
6	35	1·38	6·0	0·236	1·0	15·4
7	40 – 45	1·58 – 1·77	6·0	0·236	1·5	23·1
8	50 – 55	1·97 – 2·16	6·7	0·264	2·0	30·8

cannot be tested in this manner before use, and their cables and leads require sounder insulation. Nevertheless, they are often preferred because of their cheapness, and because a great length of the firing cable has no adverse effects; also, the diameter of the cable-wire may be comparatively small.

CHAPTER XIII

BLASTING

THE nature and compositions of various explosives have been given in the preceding chapter. It remains to discuss the procedure in shot-firing, more especially with a view to avoiding dangerous practices. In this connection the Explosives in Coal Mines Order of 1913, and the subsequent orders dealing with explosives, should be carefully studied. (See *Mining Law and Mine Management*, by Alex. Watson, in this series.)

Low Explosives. Gunpowder, black blasting powder, and bobbinite are ignited not by detonation but by a little gunpowder in the form either of safety fuse or squibs, or electric powder fuse. Safety fuse consists of a core of gunpowder protected by coverings of thread, tape, and gutta-percha. A squib consists of a tube of paper filled with gunpowder and coated with a solution of sodium silicate to stiffen it, keep it dry, and prevent it from smouldering. One end is closed by a plug, the other is twisted and coated with sulphur or saltpetre so that it may be easily ignited. The squib is made of such length that it takes 60 to 90 seconds to burn. Electric powder fuse is compulsory for igniting bobbinite in "dusty" or "gassy" mines[1]—i.e. in mines where only permitted explosives are allowed. The electric powder fuse or cap is similar in construction to an ordinary low-tension detonator (see page 131), but has a paper casing instead of a copper one, and is charged with gunpowder instead of fulminate and chlorate mixture.

Safety Fuse. Each cartridge or bobbin of explosive is hollow, being pierced by a tapering hole. The fuse is cut, and one end of it inserted into the bobbin in the manner shown in Fig. 25, the fuse being doubled over in order to bring the gunpowder of the fuse into intimate contact with the explosive, and to prevent accidental withdrawal. The shot hole having

[1] In such mines bobbinite is the only low explosive permitted.

been thoroughly cleaned out with a copper scraper (iron is not allowed) the explosive is gently inserted without disturbing the fuse from its position in the bobbin. The shot hole is then stemmed (tamped) with moist clay, the first portions being inserted gently and the remainder firmly. The length of safety fuse employed depends upon the time taken for the shot firer to retire, the fuse burning at the rate of 1 yd. in 80 to 100 seconds. (See Fourth Schedule to Explosives Order.)

To avoid blown-out shots the depth of the shot hole must not be allowed to exceed that of the undercut or holing in

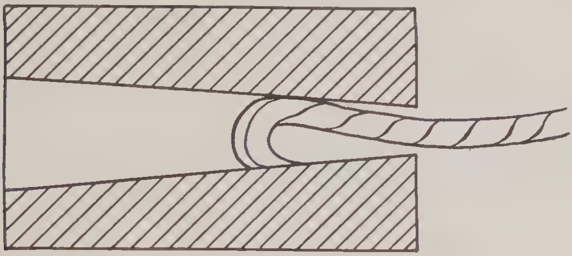


FIG. 25

the coal, except in anthracite mines (Section 6(*c*) Explosives Order).

When a squib is used for firing the (low) explosive, a pricker is pushed into the last cartridge (the primer cartridge) inserted into the shot hole. This pricker is a 4 ft. copper rod, $\frac{1}{4}$ in. diameter, pointed at one end, and having a handle at the other. The hole is them stemmed with the pricker in position, using a specially grooved copper tamping rod in order to keep clear of the pricker. When the stemming is finished, the pricker is withdrawn, leaving a $\frac{1}{4}$ in. diameter hole to the explosive charge. The squib is then inserted into this hole, and ignited with a naked light, all workmen having been removed to a safe distance.

In non-dusty and non-gassy mines explosives may also be ignited by electric detonators, by electric fuse, and by

safety fuse provided with Bickford igniter, and any of these devices may be employed if the mine is a safety-lamp mine, though non-gassy and non-dusty. Indeed, electric ignition is generally so satisfactory that it is employed to a greater extent each year, and is compulsory in "gassy" and "dusty" mines, electric powder fuse being used for low explosives (bobbinite) and electric fulminate detonators being used for high explosives (permitteds).

The Bickford Igniter (Fig. 26) is now but little used, but

FIG. 26

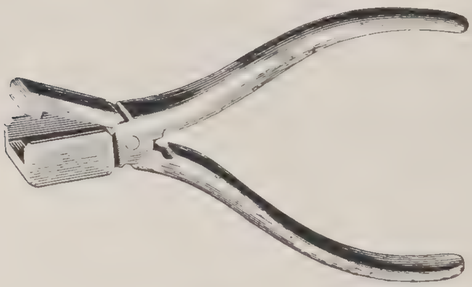


FIG. 27

its principle is interesting. Inside the metal case *A* is a glass bulb containing strong sulphuric acid, which, when the bulb is burst by the nippers shown in Fig. 27, acts on a mixture of potassium chlorate and sugar, and the heat developed ignites the fuse.

In sinking pits shots must always be ignited electrically.

High Explosives. High explosives, e.g. permitteds, are fired by a detonator, which is ignited either by fuse in naked light mines, or by electricity in gassy and dusty mines. The strength of detonator is specified on the explosive cartridge, and a weaker detonator (see Table, page 133) should never be employed, lest the charge be only partly exploded and remain afterwards as a source of danger.

In firing a detonator with safety fuse, a length of the fuse is cut square off and inserted gently into the open end of the detonator after shaking out the sawdust. The casing is then pressed near the fuse end until a secure grip is obtained, and if water is present the joint is waterproofed with grease. The wrapping of the primer cartridge is then opened, and a hole made in it with a piece of wood, such as a pencil, for over half the length of the detonator. The detonator is then inserted (see Fig. 28), and the paper wrapping folded round and tied with string to prevent withdrawal of the detonator when the cartridge is being pushed into the shot hole with the *wooden*

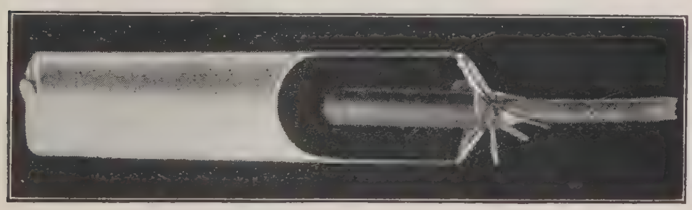


FIG. 28

tamping rod. The hole is then stemmed with moist clay as usual, and the fuse ignited with a naked light when all workmen near by have taken cover.

When *electric detonators* are used the procedure in charging the hole is similar, except that the detonator is now completely embedded in the primer cartridge, and its leads are wrapped once round the cartridge and looped as in Fig. 29.

Care must be taken not to damage the leads in stemming. After the hole has been stemmed, and all is clear, the leads are coupled to the firing cable (Fig. 30), and the shot fired from a safe distance by a magneto exploder.

Theory. To fire any detonator by electricity requires a definite amount of heat. The heat produced in the detonator is governed not only by the current passing, and the resistance of the fusehead (i.e. the wire bridge in a low-tension detonator, the priming mixture in a high-tension detonator), but also by the time during which the current passes. In symbols

$H = C^2Rt$ approximately, where H is the necessary heat energy, C the current, R the resistance, and t the time. The resistance of low-tension detonators is about 1 to 1·5 ohm, and the necessary igniting currents for a number of such detonators[1] have been found to vary from about 0·70 amp. for 0·013 sec. to about 0·45 amp. for 0·091 second. About

FIG. 29

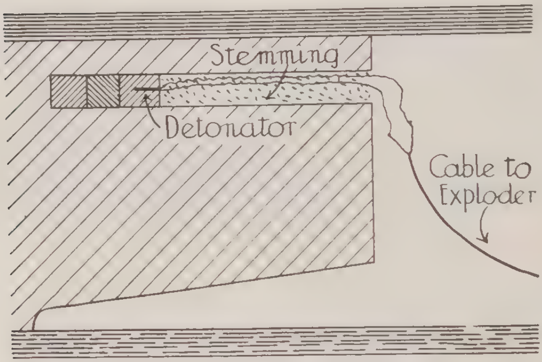


FIG. 30

0·3 amp. was the minimum current that would cause ignition when a long period was allowed. Less currents than this failed to cause ignition because heat was then lost to the surroundings more quickly than it was produced in the fusehead. With high-tension detonators similar effects were observed, but the resistance of the fusehead now varied from 2,000 to 14,000 ohms in different (high-tension) detonators, and it was found impossible to determine the igniting currents with accuracy, though they were probably less than 0·01 or 0·02 amp. It was noted, however, that the voltages necessary to fire the detonator fusehead could be reduced when longer time intervals were allowed, the actual figures varying from

[1] Safety in Mines Research Board Paper No. 11.

about 55 volts for 0·013 sec. to about 45 volts for 0·091 sec. The time element in any case, it will be seen, is small; but the above experiments have clearly shown that it does exist, and may vary from, say, $\frac{1}{100}$ to $\frac{1}{10}$ of a second, being less with the higher currents and voltages.

Magneto Exploders. These consist essentially of a horseshoe magnet (permanent), between whose poles is situated a coil of wire wrapped on an iron core capable of rotation. The coil and core are known as the armature, and the relative motion between the magnetic field and the armature wires or conductors sets up an alternating E.M.F., and hence an alternating current in the coil. If the ends of the coil are connected to two insulated slip rings, one end to one ring,

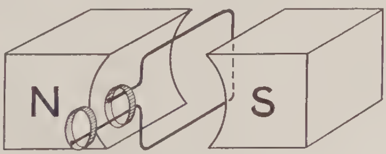


FIG. 31

the other to the other, and if these rings are both mounted on the same axis as the armature, so as to rotate with the armature, the currents generated may be led away by means of contact brushes. See Fig. 31. It is this current that is utilized to fire the detonator.

The rotation of the armature—or of the field, if so designed—is accomplished by hand. A push button in addition (for safety purposes) completes the circuit on mining instruments.

The essential difference between a high-tension and a low-tension magneto is that in the high-tension machine there are many more turns of wire on the armature, and it therefore generates a far higher voltage. This means that for high-tension magnetos, the resistance of the cable and detonator leads is negligible, no matter how long the cable may be. The only resistance of importance is that of the high-tension detonator fusehead. With low-tension exploders, however, any increase in the length of the cable or in the number of

detonators being fired simultaneously (in series) may introduce enough resistance into the circuit to prevent firing, or perhaps to fire only some of the detonators and not others.

Consequently, low-tension exploders have to be designed to generate current well in excess of the normal, though the higher the current the greater the risk of firedamp ignition. It has been shown,[1] however, that by encouraging eddy currents in the armature, by placing a band of copper round the armature core before winding, the magneto can be made safe in the

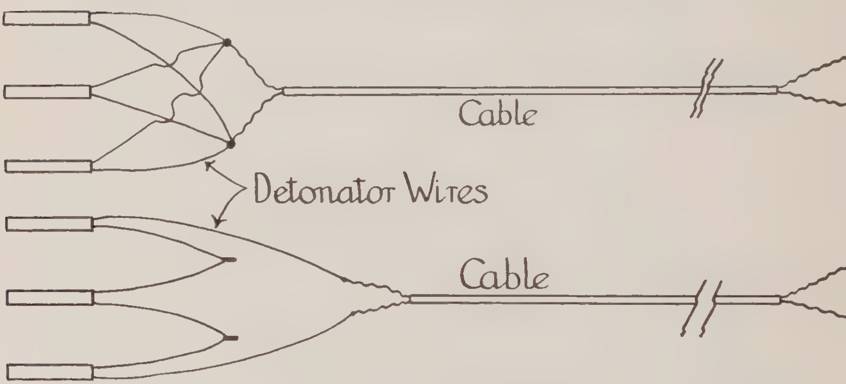


FIG. 32 *and* FIG. 33

presence of firedamp. Another method of attaining such safety consists in using a non-inductive resistance connected as a shunt across the exploder terminals.

Simultaneous Shots. These are not allowed in coal, but in stone drifts and sinkings they are commonly employed. The detonators are generally connected in series, as in Fig. 33 (lower), and this is the proper manner to connect a number of low-tension detonators. On the other hand, if high-tension detonators are employed there is much to be said for the parallel arrangement as in Fig. 32 (upper), as the voltage is now a more important factor. High-tension detonators, however, are often connected in series.

[1] Safety in Mines Research Board Paper No. 11.

In stone drifting, the shot holes may be as few as five or six in a road 7 ft. square if the strata are not hard and tough, or as many as 14 or 15 in hard rock (sandstone). The depth of the holes may be about 3 ft. 6 in., and they are drilled outwards, i.e. sloping towards the roof, floor and sides of the road as in Fig. 34.

The " centre " hole *a* is fired first, next *b b*, and finally *d d*. In general the centre hole or holes are the first to be fired, as the rock thus removed enables the shots in the other holes

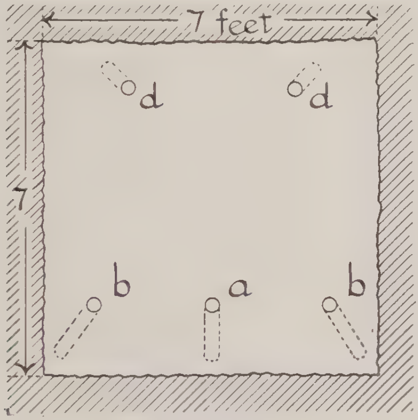


Fig. 34

to exert useful side pressure towards the centre of the drift, and thus do more effective work. In addition, the chance of a blown out shot is less. The dip and nature of the strata, however, sometimes modify the usual procedure.

In shaft sinking, similarly, the centre or sump holes are fired first, then those nearest the sump holes, and finally the outer or crown holes. The number of holes and their depth varies with the nature of the strata, but for a 20 ft. diameter shaft in ordinary ground there might be five or six sumping shots, eight to ten intermediate or breaking shots, and 20 to 30 crown shots.

Precautions when Blasting. In safety-lamp mines there is always the danger of igniting firedamp, and in all dry mines

the danger of igniting coal-dust. The following notes, taken largely[1] from the Mines Dept. S.F. Pamphlet No. 3 (1927), deal with the chief sources of danger, but the safety provisions of the complete Explosives Order should be studied and observed by all shot firers: 1. In the first place it should be noted that permitted explosives are *not* flameless.

2. Secondly, most recent firedamp explosions have been caused by firing shots when there was a break or fracture in or near the shot hole. In such breaks firedamp is often present. Consequently, the shot-firer should always satisfy himself as to their presence or absence. See Clause 6 (*d*) of the Explosives Order (1st Sept., 1913). If such breaks are found, the hole must not be charged, except in stone drifts, and then only if special permission has been given in writing by the manager or under-manager.

3. Thirdly, it is necessary to test for firedamp at all places within a radius of 20 yards immediately before firing a shot. All roof cavities must be searched for gas, if necessary with a ladder. If firedamp is present, the shot must not be fired. Moreover (to quote part of Clause 6 (*f*) (*i*) of the Explosives Order as emended on 1st Sept., 1924) "if within the aforesaid radius (20 yards) of the place there is any cavity which may contain inflammable gas and cannot be so examined, or any break where an examination cannot be made for inflammable gas issuing from it (other than inaccessible cavities or breaks in the gob, goaf, or waste) the shot shall not be fired."

4. Fourthly, with regard to coal-dust, all contiguous accessible places within a radius of five yards from the shot must be thoroughly stone-dusted or watered. If the shot-hole is within ten yards of a stone-dusted road, the stone-dusting must also extend from the shot hole to the road.

5. Fifthly, two shot-holes in close proximity must not be charged at once, or, in the words of Clause 6 (*g*) (ii) of the Explosives Order, "If two or more shot-holes have been placed in such a manner that the firing of one shot would be liable to relieve any part of the work to be done by another

[1] By permission of the Controller of H.M. Stationery Office.

shot, each shot to be fired shall be fired before any other of the shot-holes is charged."

6. Lastly, in firing a round of shots in a ventilating district the start should be made at the shot nearest the return, and so on, working always against the air. In this manner any firedamp liberated by one shot is not carried into the vicinity of a succeeding shot. It is also advisable for the shot firer to station himself on the intake side of a shot before firing it, rather than on the return side. In this way he avoids breathing the fumes of the explosive.

SUBSTITUTES FOR EXPLOSIVES

In view of the dangers attendant on the use of explosives, a number of substitutes have been put forward and tried from

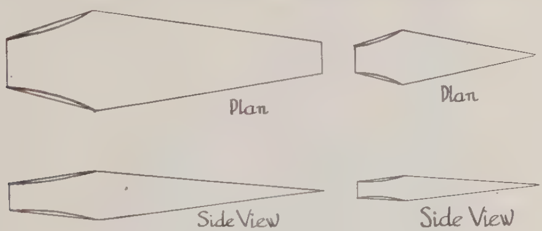


FIG. 35*a and b*

time to time, so far with very little success. The substitutes include: (1) the simple wedge, (2) the multiple wedge, (3) the roller wedge, (4) the hydraulic cartridge, (5) lime cartridges, (6) the use of SO_2, and (7) the use of liquid CO_2.

The Simple Wedge is often used for breaking down large lumps of coal or stone which have been dislodged by blasting, and sometimes for wedging down coal from the solid. These wedges are made of steel. Those used for coal (Fig. 35*a*) are larger and often much longer than those used for stone (Fig. 35*b*).

The Multiple Wedge is illustrated in Fig. 36, from which the mode of use will be clear. The borehole is about $2\frac{1}{2}$ in. diameter and 4 ft. 6 in. long. The wedge, it will be seen,

FIG. 36

consists of five pieces, the feathers or liners being first inserted. The wedge is really an attempt to reduce " metal to rock " friction by substituting " metal to metal."

The Roller Wedge, which is but little used, attempts to substitute rolling friction for sliding friction. The principle of the wedge is as follows. A middle piece whose thick end is at the back of the hole is drawn outwards by a ratchet and screw. This middle piece slides on rollers which lie between it and the two feathers which line the hole, feathers similar to those of the multiple wedge. The pulling out of the thick end of the middle piece develops pressure on the walls of the hole, and so breaks down the coal.

The Hydraulic Cartridge. Attempts have been made to utilize hydraulic pressure for breaking down coal which has been undercut.

Fig. 37 shows the arrangement of Tonge's hydraulic cartridge. A steel cylinder *a*, 3 in. diam. and 20 in. long, is fitted with 8 rams *b* which act in a steel liner *e*. There is a hand pump *c* by which water may be forced into *a* via *d*, a few strokes of the pump developing a pressure of 3 tons per sq. in. The pressure developed on *e* is said to be about 60 tons, and this fractures the coal as indicated ; *f* is a small tank for the water supply, *g* being connected to the suction side of the pump.

Lime Cartridges. Quicklime, it is well known, swells and develops great heat when moistened. These properties are utilized in the lime cartridge for breaking down coal which has been undercut. The borehole is about $2\frac{1}{2}$ in. diameter. A small iron pipe is laid along the hole and a compressed lime cartridge, grooved on one side so that it may slide over this pipe, is then inserted and the hole stemmed. Water is then pumped along the pipe from a small hand pump. The steam formed and the natural expansion of the cartridge exert a pressure which breaks down the coal.

Sulphur Dioxide, SO_2. Attempts have been made to utilize the solvent and disintegrating action of SO_2 on the coal ankerites to enable the coal to be wedged down more

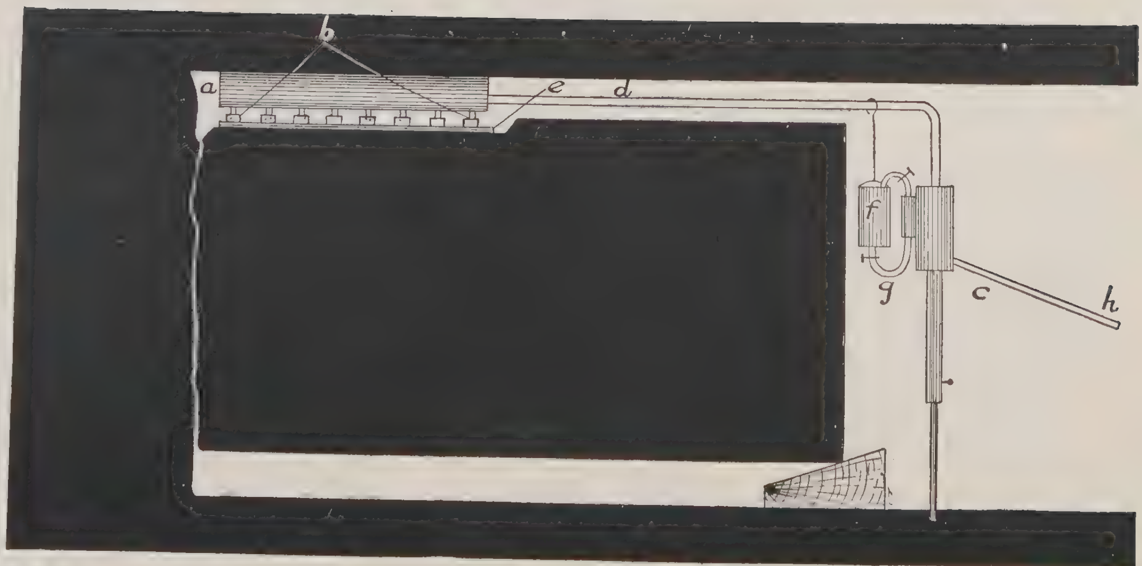


FIG. 37

easily, and so avoid the use of explosives. The SO_2 has been injected into boreholes and the action studied. Little or no success, however, has attended this method, though it is possible that with certain seams it may prove useful.

Liquefied CO_2. Carbon dioxide is a comparatively easily liquefied gas, its critical temperature being about 32° C. If heated suddenly, the liquid is transformed to gas, and a great pressure exerted if the space is confined. In certain coal mines in the United States, liquid CO_2 has recently been employed for breaking down the coal in the following manner. The liquid CO_2 is contained in a steel cylinder of 4 in. diameter and 3 ft. long, and in the same cylinder adjoining the liquid is a priming charge capable of rapidly evolving heat under the action of a powerful electric current supplied from outside. At the back of the cartridge there is a thin steel disc held in position by a screwed cover bored with a few holes. The sudden generation of gas when the current (200 amps. at about 80 volts) is switched on sheers the disc and allows the gas to escape into the shot-hole, thus wedging down the coal. The stemming, it will be seen, must be thorough, and large diameter shot-holes are required.

CHAPTER XIV

SPONTANEOUS COMBUSTION

THE fact that under certain conditions some coals are able to self-heat and ignite of their own accord has been known for many years. Thus, Dr. Plott,[1] in his *Natural History of Staffordshire*, in 1686, writes concerning certain Staffordshire coals—

. . . 'tis agreed they (various coals) all fired natural of themselves, as they expect the shale and small coal in the hollows and deads of all the old works, will doe and have done, beyond all memory. Which they say is occasion'd by a mixture of the Laming (that lyes between the measures of the coal) and the sleck (more especially when very much mixt with brass lumps) which lying together in the old cankcer'd waters of the pits, heat to that degree, that they fire the small coal left there, which continues burning till it's all spent, and then goes out of itself as soon as it comes to the rock of coal, which, if it have no rifts or clefts in it, admits it not : in-so-much that the inhabitants of these places are not concern'd at it, nor have half the dread upon them for it, that those have that live remote, far enough out of its reach. The Worshipful Dud. Dudley in his *Metallum Martis* says that small coal with sleck thrown moist together (not mentioning anything of Laming) by reason of its sulphurousness, will doe the same thing ; which I am inclined to believe, since I find amongst Dr. Powers' observations that the *Pyrites aureus* being exposed to the moist air, or sprinkled with water, will smoak and grow exceeding hot, and if many be laid in a heap and water'd, will turn red hot of themselves as he says he had seen them himself, whereof he acquaints us with a very unhappy example, that fell out at Ealand a neighbouring Town to him in Yorksh., where one Wilson having piled up many cartloads of them in a barn of his (for some secret purpose of his owne) the roof being faulty, and admitting rain water to fall copiously in amongst them, they first began to smoak, and at last to take fire and burn like red hot coales, so that the Town was in an uproar about the quenching of them. Now, if the *golden Marchasit* or brass lumps alone will

[1] Quoted in the Final Report of the Committee on the Spontaneous Combustion of Coal in Mines (1921).

thus take fire, much more will they fire when mixt with small coal: whereby as Dr. Jordan assures us whole heaps of coals mixt with this sort of *Pyrites* (call'd *metall coals*) have taken fire at Puddle wharfe in London, and at New-Castle, and been burnt before their time.

It will be seen that Plott considered that pyrites probably helped the coal to ignite, and vice versa. This will be discussed more fully later; for the present it is necessary to consider first the elementary principles involved in spontaneous combustion.

Oxidation. In Chapter IV it was shown how the rate of oxidation might be slow, medium, or rapid; and it was pointed out that the rate does not affect the amount of heat developed, but only the temperature-rise. For example, if 1 lb. of wood rots and decays entirely to CO_2 and H_2O, it gives out exactly as much heat as if it had been burnt on the fire in a few moments. But as the rotting process occupies many months and the heat is generated very slowly, there is little rise of temperature observed—if any—the heat being dissipated and carried away as rapidly as it is generated. The wood will seldom ignite, though the oxidation of decaying timber in the mine, whether coal mine or metal mine, especially in the gob, may cause a serious rise in temperature. **Dr. Haldane**[1] mentions a "place in a Cumberland haematite mine where the temperature was 40° F. above the rock temperature, owing to oxidation of old timber left behind in working by the subsidence method."

Spontaneous combustion is, then, a process of oxidation. A substance has an affinity for oxygen and absorbs it from the air. This generates a small quantity of heat and causes a slight rise in temperature, which increases the rate of oxygen absorption, and this in turn generates still more heat, causing further oxidation until the substance begins to smoulder and finally to burn. Among the common substances liable to spontaneous combustion are: pyrites, coal, oily waste, hay and wood. Substances such as phosphorous and fine iron

[1] *Trans. Inst. Min. Eng.*, Vol. LXVIII, p. 473.

powder (pyrophoric iron) are well-known to the chemist for this property, but are of little interest to the mining man.

The conditions favouring spontaneous combustion are: (1) a combustible substance with an affinity for oxygen, (2) a supply of air (or oxygen), but not so rapid as to prevent temperature-rise, (3) a large surface of the combustible substance, i.e. a powdery, or, better, a granular mass, (4) absence of good conductors of heat, i.e. a large mass, since all combustible substances and all rocks are *bad* heat conductors. Metals are the only good conductors of heat.

Spontaneous Combustion of Coal. Different coals have different capacities for absorbing oxygen, some coals, when powdered, absorbing at ordinary temperatures as much as 10 times their volume of oxygen. As a general rule, those coals which contain the most oxygen in their composition can absorb the most oxygen. The coals which have much oxygen in their composition (more than 8 per cent) are those which yield the most volatile matter; consequently, high-volatile (bituminous) coals can absorb as a rule more oxygen than low-volatile coals such as anthracitic coals and anthracites, and are more liable to spontaneous combustion. Coals, however, with high volatile matter and high oxygen content are often stronger and tougher than coals containing less volatile matter. Now the less friable the coal, the less will be the relative surface area exposed to the attack of air. It does not follow, therefore, that those coals which have the highest volatile matter and highest oxygen content are the most liable to self-heat, and many of the most dangerous coals contain only 5 per cent of oxygen and yield only 20 per cent volatile matter, expressed on a pure coal basis in each instance. Natural friability may be of the greatest importance in determining the liability of a coal to heat spontaneously.

The air supply to the coal, if too sluggish, will retard the heating by restricting the oxygen feed; and if too rapid, it will also retard the heating by preventing rise in temperature. The amount of air to produce spontaneous combustion in the shortest time is difficult to ascertain, but the quantity

which works its way to the interior of a *large* coal heap on the surface seems to be almost the optimum to cause rapid self-heating. The same is true of a badly-packed gob in the mine, through which the mine air is continuously filtering, often causing at the same time difficulties and expense in ventilating the workings. It is the small coal that is mainly responsible for the heating almost invariably. The air passes into the mass and oxidizes a little of the coal near the outskirts. This produces a slight rise in temperature, so that, as the air penetrates deeper and deeper, it becomes warmer and warmer, and though part of its oxygen has been absorbed, there is still enough to produce oxidation. Consequently, it is at some distance inside the mass that heating develops most rapidly.

It should be observed here that flame will not necessarily make its appearance, even if the coal is red-hot, as flame is due to the combustion of *gas*, and this necessitates that a moderately high proportion of oxygen be present. Thus, for firedamp to burn it is necessary to have about 13 per cent of oxygen present.

The ease with which a coal is normally ignited, as in lighting a fire, is not of very great importance in deciding its liability to spontaneous combustion ; once the oxidation process has gone beyond the early stages, and heat is accumulating, it is only a matter of time before actual ignition takes place.

Other Conditions Affecting Spontaneous Combustion in the Mine

The Temperature and Pressure of the Rocks and of the Air. These factors may exert appreciable influence on the self-heating of coal in the mine. The temperature of the strata in deep mines is always high. Thus, in a mine 700 yds. deep, the rock temperature is about 85° F. in Britain, and at a depth of 900 yds. the rock temperature is about 95° F., almost " body heat " (98·5° F.). This means that the coal starts self-heating from a better vantage point, so to speak, and

oxidation, moreover, proceeds more quickly the warmer the conditions.

Investigations by Prof. H. Briggs have shown that the heat generated in the crushing of rocks, which occurs in the gob, may be sufficient to help materially in starting the self-heating process, more especially as the same action (friction) which produces the heat tends to break up the coal simultaneously.

The temperature of the mine air approaches the natural temperature of the strata as soon as the air has travelled a few hundred yards from the downcast shaft, but the temperature may be raised still more by oxidation of the small coal of the roadways and in the gob. The pressure of the air increases with the depth of the mine, the increment being 1 in. of mercury column for every 300 yds. of descent. Consequently, the barometric pressure of the air in a mine 900 yds. deep is 33 in. of mercury, that is, 10 per cent more than at the surface. These facts must of necessity assist in the oxidation of coal in deep or moderately deep mines.

The Effect of Moisture is uncertain. A small quantity seems to assist rather than retard the self-heating of coal. This is probably due to the fact that a heap of wet coal offers far less resistance to the flow of air through it than does a heap of dry coal; pyrites is certainly more liable to oxidation when moist. Large quantities of water, however, will undoubtedly retard and prevent the heating; but alternate wetting and drying of the coal, such as occurs at the surface, appears to encourage the heating process.

Fusain, Durain, Clarain and Vitrain. It was pointed out on page 89 that the layers of ordinary bituminous coal are classified by **Dr. M. C. Stopes** into these four constituents. The fusain consists of the charcoal-like layers or pockets, known in the mine as "dant," "smut," "mother-of-coal" or "mineral charcoal": it is a soft, black powder. The durain is the dull, hard coal, sometimes known as "bone coal" or "hards." The clarain and vitrain are the shiny black coal, the difference between them being that under the microscope

the vitrain shows no spores and is more or less homogeneous. Vitrain is generally not very abundant—it breaks with a conchoidal fracture, like hard pitch.

Of these constituents, the fusain in some coals has the greatest affinity for oxygen at ordinary temperatures, but at higher temperatures vitrain and clarain have been found more susceptible to oxidation. It has been suggested, therefore, that fusain may be " the touch which sets the vitrain on fire " (**Stopes** and **Wheeler**), and that a coal is likely to be more dangerous if the fusain is embedded as pockets in the vitrain. This suggestion is borne out by recent work by **Francis** and **Wheeler,** described below. Exactly what happens, however, when oxygen is first absorbed by coal is at present open to speculation. Certain it is that at first no appreciable quantities of CO_2 or CO are given off, so that the action is either a physical solution of oxygen in the coal or a chemical addition of oxygen atoms to certain constituents of the coal substance, or perhaps both. After a while, however, the reaction is evidently chemical oxidation, heat being produced more rapidly as the temperature rises, and CO_2 and CO being evolved.

The conclusions of **Richter**, who in 1868 investigated the question of the spontaneous combustion of coals, may be mentioned here. He found that when coal absorbs oxygen, there is first a short period in which the oxygen is absorbed very rapidly, followed by a long period, generally several weeks or months, in which there is a slow absorption, provided that the temperature does not rise. He also found that part of the absorbed oxygen enters into chemical combination with the coal, and increases its weight, while part of it forms CO_2 and H_2O.

Relative Oxidizability of Coal Constituents. Recent research by **W. Francis** and **R. V. Wheeler**[1] has concentrated on finding which constituents of the coal substance are the most readily oxidizable. These authors first point out that the main chemical distinction between the fusain, durain, clarain and

[1] Safety in Mines Research Board Paper No. 28.

vitrain of a bituminous coal, " lies in the proportion of relatively 'inert' or unresponsive material with which a 'reactive' portion is associated, the 'reactive' portion being of the same chemical nature in each component." In other words, each section contains some of the same (reactive) substance, and some of a second (inert) class of substances. These inert substances must not be confused with the ash: they are merely inert in their self-heating capacity, and are essential parts of the true coal substance. The vitrain contains a very large proportion of the "reactive" substances, the clarain not as much, the durain far less, and the fusain least of all. Further, the above authors have shown that the "reactive" substances are "those that can be converted into alkali soluble ulmins[1] by mild oxidation," and that the inert portions are "the plant entities, whether resins, spore-exines, cuticles or woody tissues, that remain insoluble in alkalis after the ulmins have attained their maximum degree of solubility." Their conclusion is that "the portion of the coal conglomerate that must be held responsible for its spontaneous combustion is the ulmin portion"—i.e. in coals in which pyritic oxidation plays no important part. Coal ulmins (soluble) vary in chemical composition, the carbon being from 64 to 69 per cent, hydrogen from 3 to 5 per cent, oxygen from 25 to 32 per cent, and nitrogen from 2·20 to 2·25 per cent.

To find the proportion of ulmic compounds present, it is necessary to oxidize the coal in order to convert the compounds to the soluble state. This may be done by prolonged exposure to a stream of air at about 150° C., or more easily by treating the coal with hydrogen peroxide (H_2O_2) or dilute nitric acid (NHO_3). The oxidized coal is then treated with a solution

[1] Ulmins or humic compounds are the organic acidic products of decay of vegetable matter found in peat bogs, etc. They can be extracted from coal, peat, lignite, etc., by alkaline solutions, such as caustic potash. Fresh bituminous coal contains only a trace of ulmins soluble in (alcoholic) caustic potash solution, but on oxidation of the coal the soluble ulmic proportion increases, especially that of the vitrain and clarain layers. The "ulmin portion" of a coal is that portion which on oxidation gives rise to soluble ulmins. Francis and Wheeler have shown that it is essentially the ground-mass of the bright coal (clarain and vitrain) which is the ulmin portion.

of caustic potash (in alcohol) and the proportion which dissolves is regarded as ulmins. The higher this proportion, the more liable is the coal to self-heating. In passing, it may be noted that oxidizing the coal with air (or with H_2O_2 or HNO_3) is essentially reversing the process of coal-making from vegetation ; and this reversal is naturally more easily effected with lignites and bituminous coals than it is with anthracitic coals and the like, as the latter have a chemical constitution further removed from that of ordinary vegetation. The formation of coal from "wood" is essentially a process of "reduction," i.e. removal of oxygen : the formation of "wood" from coal is thus one of oxidization. The calorific value of fully-oxidized coal[1] is less than the normal value for the unoxidized coal by about 20 per cent (for vitrain) or 10 per cent (for durain). Ordinary weathering, it may be mentioned, lowers the calorific value by 1 to 5 per cent in the first year and by an additional 1 per cent for each succeeding five years up to a maximum reduction of 10 per cent. But different coals may give widely different results.

The Quantity of Heat Generated. **Winmill**[2] has found that when coal (Barnsley Bed) absorbs oxygen at ordinary temperatures, heat is generated at the rate of 2·1 calories per cubic centimetre of oxygen absorbed, i.e. 236 B.Th.U. per cubic foot of oxygen absorbed. He has also found that pyrites plays little part in the spontaneous combustion of this coal, and other researches have confirmed his view. The specific heat of coal when quite dry is about 0·25. If the natural moisture content of the Barnsley Bed be 10 per cent, the specific heat of the whole coal becomes $(0{\cdot}90 \times 0{\cdot}25) + (0{\cdot}10 \times 1{\cdot}0) = 0{\cdot}325$. Hence, when 1 ton of the coal absorbs 10 cub. ft. of O_2, the temperature rise is $\dfrac{236 \times 10}{2240 \times 0{\cdot}325} = 3{\cdot}24°$ F., if there is no loss of heat to the surroundings ; and Winmill estimates that in such circumstances, i.e. no loss of heat, the Barnsley Bed coal will fire in a minimum of about

[1] Safety in Mines Research Board Paper No. 28.
[2] *Trans. Inst. Min. Eng.*, Vol. XLVIII, p. 510.

8 days (see Table on page 157). Coal has a calorific value of about 14,000 B.Th.U. per lb., and 1 lb. of coal requires about 140 cub. ft. of air or 30 cub. ft. of oxygen to burn it. Hence, the heat emitted per cubic foot of oxygen used in ordinary burning is about 470 B.Th.U., that is, twice the heat produced by the absorbtion of 1 cub. ft. of oxygen in the early stages of self-heating.

The influence of moisture on the specific heat of the whole coal is seen in the calculation above, but when the water is actually evaporated by the heating mass, its cooling influence is still more marked, especially at temperatures approaching the boiling-point, e.g. 70–80° C., 158–176° F. Below 70° C. the cooling effects due to the absorption of latent heat by the steam, while present, are not of much importance. At 70° C. however, half the heat produced from the oxygen absorbed from the air-current (when the issuing stream contains no oxygen) will be required to evaporate the water. At 80° C. the heat produced by the absorption of "all the oxygen[1] in the air supply is needed to evaporate water, and hence the temperature can not rise above this point until all the water has disappeared. Provided that it survived this interval, the temperature would afterwards begin to rise rapidly again, increasing in rapidity until the coal fired. This is shown by Table XIX, which is based on the assumption that all the oxygen is absorbed from the air stream, which is saturated with moisture when it leaves the coal."

"The difference between the two rates indicates how 'exact' the conditions have to be for a small mass of coal actually to fire. The air-current must be regulated to a nicety and the mass must be well heat-insulated."

Incidentally, Winmill also found that the fusain of the Barnsley Bed was a comparatively poor absorbent of oxygen, but different fusains apparently show different activities in this respect, as found by **Tideswell** and **Wheeler**.[2]

[1] Winmill, *Trans. Inst. Min. Eng.*, Vol. XLVIII, p. 519.
[2] Tideswell and Wheeler, *Trans. Chem. Soc.*, 1919, Vol. CXV, p. 633.

TABLE XIX (Winmill)

Rate of Heating of Barnsley Hards

Temperature ° C.	Hours (water[1] evaporating from the coal)	Hours (no water evaporating from the coal)
30	0	0
40	7	7
50	18	18
60	28	27
70	44	35
80	79	43
90	171	48
100	183	51½
110	188	52½
120	190	—
130	191 (8 days)	54

The Action of Pyrites. The brassy lumps or layers which occur abundantly in certain coal seams, and are present to some extent in all, are a compound of iron and sulphur (FeS_2) known as iron di-sulphide or pyrites or "brasses." Pyrites occurs in coal in a variety of forms,[2] namely, as balls, as lenticular masses, as layers, and as specks which may or may not be visible to the naked eye. The colour of the pyrites also varies; it may be brassy yellow or golden yellow, or dull grey, silver grey, or greenish grey. And of these types at least two main crystalline forms are known, one the cubic variety, and the other the rhombic or marcasite variety.

Now, experiments and observation have shown that certain of the above types are more liable to oxidation than others; e.g. the rhombic varieties are usually more easily oxidized at ordinary temperatures than are the cubic varieties; but probably they are all oxidizible, provided first that the pyrites crystals or particles are broken down to powder, and secondly that moisture is present. Air or oxygen must, of course, always have access.

[1] The natural moisture content of the "hards" investigated by Winmill was about 5 per cent.

[2] For details, coloured photographs, and further information, see Safety in Mines Research Board Paper No. 26.

When pyrites suffers oxidation in the presence of water, the composition of the substances formed depends upon the stage which the oxidation has reached. As a rule, the main reaction is that indicated by the equation—

$$\underset{\text{pyrites}}{2FeS_2} + \underset{\text{oxygen}}{7O_2} + \underset{\text{water}}{2H_2O} = \underset{\text{sulphuric acid}}{2H_2SO_4} + \underset{\text{ferrous sulphate}}{2FeSO_4}$$

If the oxidation proceeds further, ferric sulphate [$Fe_2(SO_4)_3$] may also be formed, as well as some sulphur dioxide (SO_2) and free sulphur (S). The free sulphur, however, would soon be oxidized to sulphur dioxide, even if the temperature were only as high as 60° C., well below the boiling point of water. Where oxidation of pyrites is proceeding, therefore, one may expect: (1) an acid mine water, corrosive to pipes, pumps, rails, and all iron work; (2) incrustations of ferrous sulphate crystals (pale green), and (3) if carbonates of calcium, magnesium or iron are present near the pyrites deposits of ferric hydroxide (yellowish-brown) and sulphates of calcium and magnesium (white or in solution). At the same time CO_2 is liberated. The white flakings in coal, generally best developed along the vertical cleavage faces, are called coal-ankerites; they are carbonates of calcium and iron, and if an acid water acts on such a carbonate CO_2 is naturally liberated.

Heat Generated by Pyrites. The heat produced when pyrites absorbs oxygen and forms ferrous sulphate and sulphuric acid as indicated by the equation above is about 4·3 calories per cubic centimetre of oxygen absorbed—i.e. 484 B.Th.U. per cubic foot of oxygen absorbed, roughly twice the heat produced by the absorption of the same quantity of oxygen by coal; and as certain forms of finely-divided pyrites absorb oxygen far more rapidly than coals do, pyrites may in these coals be the chief factor in starting combustion. On the other hand, it has been shown that certain coals, comparatively rich in pyrites, are not by any means readily susceptible to spontaneous combustion, and it is considered nowadays that only with a few coals does pyrites play a vital

[1] Winmill, *Trans. Inst. Min. Eng.*, Vol. LI, p. 503.

part in starting the heating process. With most coals the rise in temperature produced by pyritic oxidation must be almost negligible, first because of the small quantity of pyrites present, about 3 per cent generally, but perhaps up to 10 per cent in the " small coal " left in the gob, and secondly, because the heat generated will not be all concentrated at one point. Therefore, while pyrites may occasionally be an important factor in the initial stages of spontaneous combustion, by causing a serious rise of temperature, it is not generally so. Nevertheless, if pyrites is spread as grains throughout the coal, it is a source of danger, inasmuch as it is easily liable to oxidation, and in oxidizing it swells, breaks up the coal, and exposes fresh surfaces to the air. This is probably the main rôle which certain forms of pyrites play in promoting the spontaneous combustion of coals.

Bacterial Action—Haystacks. It has been suggested by some that the self-heating of coal in the incipient stages may be due to bacterial action, but there is little evidence to support this view, and it is now seldom put forward.

Bacterial action, however, is responsible for the early stages of self-heating which occur in haystacks and the like, and occasionally cause the stacks to fire, more especially if the grass has been stacked in a moist or only partially-dried condition. " Dry " grass contains about 15 per cent of moisture ; incompletely-dried grass may contain twice as much. According to **Prof. Miehe** of Leipzig (1911), the fermentation which begins immediately the stack is made is due mainly to the action of certain bacteria of the Bacillus Coli type, which flourish at ordinary temperatures, and up to 42° C. (i.e. 108° F.). Above this temperature Bacillus Coli is unable to live, but it gives place to an organism of the Bacillus Calefactor type, which flourishes between 30° C. and 62° C. (i.e. 86° F. and 144° F.). These latter bacteria consequently carry on the fermenting and heating process to a temperature of 62° or 63° C. Beyond this, any further heating is apparently due to chemical oxidation[1] and it thus

[1] Haldane and Makgill, *Fuel in Science and Practice*, December, 1923.

resembles closely the ordinary self-heating of coal. Incidentally, Haldane and Makgill point out that accompanying the biological heating and independent of it, there is in damp hay a heating effect due to chemical oxidation, but that at ordinary temperatures it is completely overshadowed by the bacterial heating. The chemical action, however, increases rapidly with rise of temperature, as usual.

A haystack generally fires near the centre if it fires at all. This is because the heat is carried away by air currents from the outside layers, but further into the stack the heat tends to be insulated and, provided that air can find access, combustion will probably start there. Charring in the interior of a stack is commoner than actual burning, and it is often only on cutting into a heating stack that the material actually bursts into flame.

Summary. As already stated, however, bacterial action is not of importance in the heating of coal, if, indeed, it is concerned at all. The coals most liable to self-heat are those which (*a*) have the greatest affinity for oxygen, (*b*) are most friable, and (*c*) contain certain easily oxidized forms of pyrites ; and, as a general rule, those coals have the greatest affinity for oxygen which yield on distillation the most volatile matter and have a high natural moisture content. Lignites, if the mines be dry, are very liable to cause gob fires ; anthracites, on the other hand, are practically immune.

CHAPTER XV

GOB FIRES—TREATMENT AND PREVENTION

TREATMENT OF GOB FIRES

Symptoms of Gob Fires. One of the earliest and most reliable indications of dangerous self-heating of coal in the mine prior to a gob fire is "gob stink," i.e. the odour of the gases and vapours given off. The smell in the earliest stages of the heating is not unlike that of rotting vegetation with a faint odour of onions. Later, it is more like a "gasworks" smell, and still later it becomes "sharp" in the nose and eventually unbearable. Headache is experienced, generally after work, probably due to breathing traces of CO and H_2S.

Another reliable indication of dangerous heating is the "sweating of the strata." This is merely the condensation of the water vapour given off from the heating coal, on the roof, floor, and sides of the roadways nearby, or on any other adjacent material. Hygrometer readings are especially useful in locating incipient gob fires, because of the emission of much water vapour, which, combined with a rise in temperature, results in abnormally high wet bulb readings. A sensitive thermometer alone is also useful.

The gases given off in the early stages of heating are CO_2, CO, and H_2S. Of these, H_2S is perhaps the most readily detected, due to (1) its smell of rotten eggs, and (2) its action on white blotting paper which has been dipped into a solution of lead acetate, $Pb(CH_3COO)_2$. To this it gives a black or dark brown metallic tarnish, due to the precipitation of lead sulphide, PbS. It is to be noted that the usual smell of H_2S is often masked in "gob stink"; hence the necessity for the lead acetate papers.

CO_2 and CO are also found as just stated, but the CO is generally present in the air only in traces, from 0·02 to 0·2

11—(5471)

per cent or more in bad cases. The actual amount present may be estimated by Graham's[1] apparatus, or by fractional combustion[2] in the Haldane apparatus, the CO_2 and O_2 present being also obtained when using the latter apparatus. In the mine, however, a few birds or mice are the best indicators of dangerous amounts of CO, or any other poisonous gases, and have to be used where men are at work near gob fires, e.g. in sealing them off.

Another indication of spontaneous combustion is the dimming of the lamp flame due to lack of oxygen in the air. It will be remembered that a drop of 1 in the percentage of oxygen causes a drop of 30 per cent in the candle-power of the flame, even if the flame is still large, and when the oxygen falls to about 17·5 per cent, the flame is extinguished. Naked lights behave similarly.

At later stages of heating, smoke appears; and after a period, varying from a few days to several weeks after the first indications, actual burning at red heat takes place. The above is, briefly, the record of all gob fires, though in some only a few of the indications mentioned may have been noticed.

Treatment of Gob Fires. If the fire has not broken out, it may be possible, if at the very outset, to cool down the affected area by increasing the ventilation; but once the heating has gone beyond the incipient stages, and it generally *has* before it is detected, it is futile to hope to cool down the heating coal by increasing the air supply. It will have precisely the reverse effect. On the other hand, if the ventilation be reduced, there is danger in a "gassy" seam that firedamp may accumulate, give an explosive atmosphere, and the mixture become ignited by the hot material. In "gassy" seams, therefore, it will probably be best to maintain the ventilation at its usual amount, but in seams where little or no firedamp is found the proper course is to reduce the supply of air to a minimum by slowing down the fan or using regulators or the like.

[1] *Journal of Society of Chemical Industry*, 1919, Vol. XXXVIII pp. 10–14T.

[2] *Fuel in Science and Practice*, 1925, pp. 450–454.

If it is a small fire easily accessible and the roof is moderately good, the best procedure is to dig out the hot material at once, quench it with wet sand or soil, and send it out of the pit in iron tubs. In gassy mines this can only be done with safety if the heating is only just beginning and therefore of small extent. If digging out be impracticable, it is common to dam or seal off the district with brick stoppings (see Fig. 38) built well into the sides, roof, and floor, and packed solidly with sand, soil, stone-dust, and the like, in order to make a

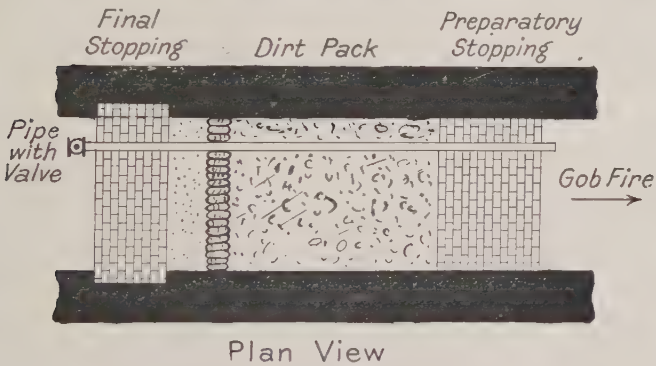


FIG. 38. GOB FIRE SEAL

thorough seal. In seams liable to gob fires, these stoppings are generally prepared well in advance, so that to seal off the district is the work of only a few hours. This, however, will not extinguish the fire at once, because of the large volume of air enclosed ; and if firedamp is being given off in any quantity an explosion is by no means improbable. Indeed, such explosions have occurred in many mines within an hour of sealing off, the intake and return sides of the fire being sealed simultaneously, and are most common if the sealing operations have taken several days to complete.

Construction of Temporary Stoppings. Arguing from this observation, **E. O. Simcock**[1] pleads for the insertion of temporary stoppings as near to the fire as possible, the stoppings

[1] *Fuel in Science and Practice*, March, 1925.

being constructed of boards covered, on the fire side, with a layer of moist fireclay or marl, the layer being about 1 ft. thick at the bottom, tapering to 3 or 4 in. at the top. If boards are not substantial and fireproof enough, he recommends ordinary pit props in their place along with the wet clay, the latter being the real seal. "It may seem," he says, "to most practical pitmen that such a stopping would be useless, or could be used only in urgent necessity. I agree that the first time I used such a stopping it was through urgent necessity, but its surprising efficiency when first used in quickly bringing the fire into complete control caused similar means to be used again until it became my invariable practice to use them as a first operation at any gob fire. The subsequent operations of building permanent stoppings followed when convenient and not necessarily immediately. In no instance within my experience was gas fired in the area enclosed by these stoppings, although there were several critical cases of so bad a character that it would have meant abandoning whole districts had the building of permanent stoppings been attempted at the first stage."

Where the conditions warrant it, and it is a practical proposition, it may be advisable to flood the affected area with water, though this is usually only a last resort if a large district is involved. Flooding an underground district with CO_2 has also proved successful in a few mines, the CO_2 being supplied from numerous cylinders placed around the affected area.

In North Staffordshire, where gob fires are common, it is the ordinary practice to work the seams to the dip and allow the gob to become filled with firedamp. Such a practice has been found reasonably safe and effective, as when the gob is full of gas the air has but little access.

Explosions After Sealing-off. When a fire has been sealed off, the oxygen of the air shut in begins to be absorbed by the fire, and firedamp (CH_4) and perhaps other inflammable gases, including CO, H_2S, and H_2 may be given off. As soon as there is about 5·4 per cent of CH_4 present, the atmosphere

becomes explosive, assuming that there has been no serious drop in oxygen content. If, however, the oxygen has been absorbed in large quantity, the lower limit of inflammability will be reached when about 6 per cent of CH_4 is present ; but if the oxygen be less than 13 per cent, the mixture will be non-inflammable, unless serious quantities of CO or H_2 are present, which is unlikely. On the other hand, even if no appreciable absorption of oxygen takes place, the atmosphere will cease to be inflammable if there is present more than 15 per cent of firedamp, again assuming the absence of serious amounts of CO and H_2. In the interim, however, while the firedamp proportion is increasing from 5·4 to 15 (or less if much oxygen has been absorbed), explosions are likely and almost unpreventable, but they need not have serious consequences. As already pointed out, a firedamp explosion in itself is not a violent and terrible occurrence ; the main danger is that it may initiate a coal-dust explosion. Now, this can be avoided either by thorough watering of all roadways in the vicinity, or preferably by thoroughly stone-dusting them until there is 75 to 80 per cent of stone-dust present, in order to ensure perfect safety. A large body of firedamp and air in explosive proportions is unlikely behind the stopping, as blackdamp is being continually produced, and the puffs or small explosions often noticed while the stoppings are being built are only indications of danger if the seam gives off firedamp very rapidly in proportion to the rate at which the oxygen is being absorbed.

Fresh air should always be fed by air pipes or the like to men working on the return side at building the stoppings in order (1) to maintain a non-explosive atmosphere there, and (2) to prevent poisoning or fatigue, due to the presence of CO, H_2S, and CO_2 in the air.

Sealing-off.[1] " The stoppings should be so constructed that free air passages or openings, sufficient to reduce to a harmless percentage the gas in the open workings of the section to be sealed off, should be left till the last moment and the openings

[1] *Trans. Inst. Min. Eng.*, Vol. LXIX, p. 429.

then quickly closed by doors, packs, or other ready means, the stoppings on intake and return sides being thus closed simultaneously by trustworthy men, who will afterwards withdraw to a safe position. By this means, risk to life during the erection of stoppings will have been reduced to a minimum. If, unfortunately, an explosion sufficiently violent to damage a stopping should occur, this will probably be at only one stopping, leaving the air supply sufficiently restricted to prevent the air from again becoming inflammable.

"A period varying from about 24 hours, when the space shut off is very large to an hour or less when it is small, ought to be allowed to elapse before the stoppings are again examined after closure, or after an explosion, since a second explosion might follow. A sample, obtained through a pipe in the stopping, should then be taken on the return side to ascertain that the air inside is no longer inflammable, and a water-gauge reading to the pipe should be read. The stoppings may now be completed in a more permanent manner."

Finally, it should be noted that the stoppings should be as airtight as possible, and that double stoppings on each side of the fire have great advantages over single ones, as black-damp accumulates between them and acts as a buffer not only to any explosion flame coming from the fire, but also on the other side to fresh air, which always tends to leak in towards the heating material.

PREVENTION OF GOB FIRES

The Method of Work

Ordinary Longwall. Various systems of working seams liable to spontaneous combustion are adopted, but where practicable, ordinary longwall would seem to be the best if special precautions are taken. These precautions include: (1) keeping the face straight and its rate of advance regular, (2) maintaining airways of large cross-sectional area, and (3) carrying the roads well above the level of the gob by doing extra ripping in the roof. This last precaution is very desirable where seams over 4 ft. thick are worked, in order

to prevent leakage of the air through the badly-packed gob. All abandoned roads should be packed as solidly as possible, the packing in the gob should be thorough, and small coal and timber should never be used in the construction of the packs. The number of gate roads employed should be the minimum, but several ventilating districts or "splits" are desirable in order that the ventilation may be effected with a low water gauge or pressure difference between intake and return, and consequently with less leakage through the gob. Where air filters through a number of fine pores, such as through a bed of sand, or slack and coal-dust, the amount that passes varies directly as the pressure; whereas when air flows along a pipe or airway, the amount that passes varies as the square root of the pressure. Consequently, if the ventilating pressure be halved, the leakage (assuming the channels are of very small cross-section, say, $\frac{1}{16}$ in. square) will be halved, but the roadway air flow will be reduced to $\left(\frac{1}{\sqrt{2}}\right)$ of the original, i.e to 0·707 of the original. If the ventilating pressure be reduced to $\frac{1}{4}$ of the original, the leakage will become $\frac{1}{4}$ of the original, and the air flow in the roadways $\left(\frac{1}{\sqrt{4}} =\right)$ $\frac{1}{2}$ of the original.

Where **faults** are encountered, special care is necessary. Faults are a source of danger, inasmuch as (1) they interfere with the general advance of the face, and so cause irregular subsidence in the gob, (2) they are planes of weakness and are consequently associated with cracks and cavities in the roof where air may gain access, and (3) they cause a certain amount of coal near them to be left unextracted. This coal is often a source of subsequent trouble, as it readily heats because of its soft, friable nature. Where faults are met, therefore, as much as possible of the coal should be extracted, and the packing in the vicinity should be made as sound as possible.

Falls at the Face. When large falls occur at the face, a considerable amount of coal and timber is often left buried,

and it has been noticed that these places are generally the sources of gob fires later. The places where such falls occur should therefore be recorded in a special book, and at the same time every effort should be made to remove as much as possible of the coal and timber and to fill all cavities with soil and shale and stone-dust. If there were less coal left in the gob, gob fires would be far more rare. It is generally with thick seams, i.e. with seams 4 ft. or more in thickness, that gob fires are prevalent. This is due to a greater amount of coal being left in the gob and also to the natural difficulties in packing thick seams. **Longwall Retreating** is sometimes adopted with advantage as a method of working seams liable to spontaneous combustion, especially if they are very gassy.

Panel System. In other mines, the method of work favoured is the *panel system*, in which the area of coal to be extracted is divided into a number of panels, which are worked independently. The system of work for each panel may be either longwall or pillar and stall. Each panel is opened up from two roads, which are provided with a short length well bricked and equipped so that in case of emergency the rapid sealing-off and isolation of a panel can be accomplished in a few hours. The sealing of one panel does not affect the working of the other panels ; but it frequently happens that on reopening a panel, which may have been sealed for years, the gob fire again breaks out.

Hydraulic Stowing of the gob has been adopted with success in the Fifeshire coalfield as a method of preventing gob fires. Where plentiful supplies of sand and gravel are available, the conditions may warrant the introduction of this excellent method of stowing the gob, but in many mines it is doubtless impracticable. Nevertheless, there are others where it could be adopted, and where it would prove beneficial in completely eliminating gob fires.

Organization: Mine Air Testing and Analysis. Much can be done to assist in detecting potential gob fires by proper organization at the mine. All workmen should be requested and encouraged to report to the fireman any indications, such

as a peculiar smell, a rise in temperature, or sweating of the strata ; and if the indications are verified by the fireman, he should at once report to the under-manager or other official whose duty it is to investigate suspected heatings. In some mines it is necessary to appoint special officials for this purpose.

Where the indications are doubtful, careful temperature and hygrometer readings should be taken, and full analyses of the air should be made. Indeed, in all mines liable to spontaneous combustion the return air in all splits should be regularly tested and analysed, and the results carefully scrutinized. A reduction of the oxygen content or an increase in the CO_2 or in the CO should be regarded as indicating danger ; and any unusually high temperature or humidity should be interpreted similarly.

Traces of H_2S are best detected by lead acetate papers, used in the mine as already stated, since the ordinary smell of H_2S is often masked ; and to detect small quantities of CO, Graham's apparatus or fractional combustion in the Haldane pipette may be employed. As little as 0·2 per cent of CO may prove fatal if breathed for more than one hour, and even 0·1 per cent may be dangerous to a man working or walking in such an atmosphere.

Breathing apparatus for rescue work, described in the next chapter, have proved most useful in enabling men to seal off gob fires in atmospheres poisonous with CO or H_2S, or irrespirable from any other cause.

CHAPTER XVI

BREATHING APPARATUS FOR RESCUE WORK

The foregoing chapters of this book have treated of the *prevention* of explosions, and it is to be hoped that as scientific knowledge and engineering technique improve there will be little necessity to discuss the aspect of mine explosions with which this and the following chapter will deal. At the present time, however, as large mine explosions still occur, though in Great Britain less and less frequently year by year owing to scientific research, it is necessary for the mining man to understand the special breathing apparatus employed when penetrating poisonous atmospheres and also to be aware of the best procedure immediately after an extensive explosion.

Breathing apparatus may also have to be used by men fighting a gob fire, so that the use and construction of such apparatus is of double importance. Before describing some of the better types of approved breathing apparatus, however, the process of respiration, outlined on page 38, must be explained more fully.

Respiration supplies oxygen to the blood and thus to all parts of the system, and removes at the same time the carbon dioxide carried back to the lungs by the blood in the veins. When work is done by the body, the normal rate of tissue destruction is increased, and CO_2 is therefore produced in greater quantity and more oxygen is consumed, all of which are effected by increased breathing and increased blood circulation. From researches by **Haldane** and **Priestley**, it would appear that[1] " *under normal conditions*, when resting, the factor controlling the breathing is the concentration of CO_2 in the blood. The part of the brain, known as the 'respiratory centre,' which directs the movements of the lungs,

[1] Second Report of the Mine Rescue Apparatus Research Committee, 1920, p. 7.

receives its incentive from the CO_2-saturation of the blood passing through it, and it controls matters with an almost inconceivably delicate degree of regulation, so as to maintain that saturation at a constant level. If the blood should become over-concentrated in CO_2, enhanced breathing (hyperpnoea) results, and continues until the excess is removed; if for any reason the degree of saturation is reduced below normal, there is a cessation of breathing (apnoea) until the deficiency disappears." It is CO_2, then, and not oxygen, which governs the respiratory rate, and this is the reason why oxygen with about 3 or 4 per cent of CO_2 is the best mixture to use when restoring respiration artificially.

The presence of oxygen in the air breathed is, of course, essential, but CO_2 in the lungs is equally necessary, and is, as just stated, the factor which governs the rate of breathing. In a normal healthy man, the percentage of CO_2 in the air in the lungs (alveolar air) is about 5·6; and if the CO_2 in the inhaled air approaches this figure, fatal results may ensue. Indeed, 3 per cent of CO_2 will produce very deep breathing, and 4 to 6 per cent will, on exertion, bring about collapse after a while.

The effects of oxygen shortage are different; instead of being gradual and causing deeper breathing, the effects are rapid and the breathing becomes quick and alternately shallow and deep, and collapse soon follows. Lack of oxygen, then, is far swifter in causing collapse, than is excess of CO_2, and it gives little or no warning.

The amounts of oxygen consumed and CO_2 produced in breathing and other useful data, are shown in the following table, taken from a paper on "Physiological Observations on Pike's Peak," by **Douglas**, **Haldane**, **Henderson** and **Schrieder**. It is well to note here that walking at 4 or at 5 miles per hour is equivalent to the hardest of manual labour performed by the body; the exertion required in walking tends to be underestimated merely because "walking" is not usually regarded as "working." To convert the figures to British measures, it is useful to remember that 1 litre = 1·76

pints = 61 cub. in. The volumes are calculated to their equivalent values at 0° C. and 760 m.m. mercury pressure.

TABLE XX. RESPIRATION DATA

Amount of Exertion	Number of breaths per minute	Average volume of each breath (in litres)	Volume of air breathed per minute (in litres)	Volume of oxygen consumed per minute (litres)	Volume of CO_2 given off per minute (litres)
Standing at rest .	17·1	0·612	10·4	0·328	0·264
Walking 2 m.p.h. .	14·7	1·271	18·6	0·780	0·662
,, 3 ,, .	16·2	1·530	24·8	1·065	0·922
,, 4 ,, .	18·2	2·060	37·3	1·595	1·398
,, 5 ,, .	19·5	3·145	60·9	2·543	2·386

It will be seen that the volume of air inhaled at rest is about (0·6 × 61 =) 35 cub. in. per breath ; this is called the "tidal air," in contrast to the residual air remaining in the chest. On exertion, however, 3 or 4 times the above quantity can be taken in per breath, and as the number of breaths per minute may rise from 15 to 20, the total volume of air breathed per minute may be 5 or 6 times the volume breathed at rest. It will also be seen that walking, even at the slow rate of 2 miles per hour doubles the oxygen consumption.

Oxygen Used and CO_2 Formed in Respiration. The CO_2 produced is from 0·8 to 0·9 of the oxygen consumed, except when doing the very heavy work equivalent to walking at 5 miles per hour, in which case it rises to 0·94 of the oxygen consumption. In doing the heaviest of work, a man may produce for a while a larger volume of CO_2 than that of the oxygen absorbed,[1] but as an approximate rule we may assume that the volume of CO_2 produced will generally be slightly less than that of the oxygen absorbed, since some of the oxygen is normally used up in producing H_2O and other oxidation products in the body.

A man on moderate exertion, then, may consume up to 2 litres (122 cub. in.) of oxygen per minute, and it is compulsory

[1] See Technical Paper 82, U.S.A. Bureau of Mines, "Oxygen Mine Rescue Apparatus and Physiological Effects on Users," by Yandell Henderson and James W. Paul.

in Great Britain that all approved self-contained breathing apparatus shall supply oxygen at not less than 2 litres per minute (General Regulation, 1920, No. 1423).

Absorption of CO_2 in Breathing Apparatus. The CO_2 given off in breathing has to be absorbed if the breathing circuit is to be self-contained, i.e. unless the exhaled breath is allowed to escape through a valve to the open air. Such escape would mean a great loss of oxygen, as there is normally from 16 to 19 per cent of oxygen in the exhaled breath if a man is breathing air, and more than 90 per cent if he is breathing nearly pure oxygen. The usual practice, therefore, is to absorb the CO_2 by caustic soda (NaOH) sticks or granules, or by coke which has been impregnated with a solution of caustic soda. Caustic potash (KOH) is also a good absorbent, but is more expensive. The absorption of CO_2 may be represented by the following chemical equation.

$$\underset{\text{caustic soda}}{2NaOH} + CO_2 = \underset{\text{sodium carbonate}}{Na_2CO_3} + H_2O$$

It will be seen that water is produced. Heat also is developed by the absorption, and unless this is dissipated, the temperature and humidity of the inhaled gases may rise to a dangerous degree. Hot moist air causes a burning sensation in the throat; indeed, an apparatus is regarded as unsatisfactory if the temperature of the inhaled air exceeds the temperature of the outside air by more than 20° C. It is important, therefore, that the apparatus should be so designed that the heat generated in the purifier, i.e. in the vessel containing the caustic soda, should be rapidly dissipated or absorbed to prevent rise of temperature; and it is also important to avoid contact of the purifier with the body or clothes of the wearer, as the purifier temperature may be high enough to cause serious discomfort.

Further Requirements of Breathing Apparatus. 1. The apparatus should be capable of being used for a reasonable length of time. The period specified by the present regulations is 2 hours, the rate of oxygen supply being not less than 2 litres per minute.

2. The purifier containing the caustic soda for absorbing the CO_2, should be capable of outlasting the oxygen supply. A purifier is regarded as satisfactory if there is not more than 2 per cent of CO_2 in the inspired air at the end of a 2-hour period of hard work, such as walking at 4 miles per hour.

3. A reservoir of " air " is necessary in order that the wearer may take deep breaths without creating a partial vacuum inside the apparatus. A rubber-lined breathing bag, from which the " air " is directly inhaled, is employed for this purpose. Collapse of the breathing-bag, either through leakage or failure of oxygen supply or faulty release valves has probably caused certain fatalities in the past.

4. There must be no great resistance to breathing, or CO_2 will begin to accumulate in quantity in the lungs and in the arterial blood. Moderate resistance is easily compensated for automatically by the body, but with high resistance in the breathing circuit the breathing becomes rapid and shallow, and symptoms of asphyxia follow. It is suggested[1] that the resistance should not be more than that represented by 3 in. of water gauge (15·6 lb. per sq. ft.) when the air flow through the apparatus is at the rate of 3 cub. ft. (85 litres) per minute.

5. The apparatus must be gastight and of sound and sturdy construction. Compressed oxygen apparatus are generally tested for leakage by complete immersion in water, the oxygen being turned on and the mouthpiece closed.

6. The mouthpiece connections to the mouth of the wearer must be leak-proof, and not capable of being accidentally displaced. The nose clip must prevent all breathing through the nose, and also be incapable of being accidentally displaced, as is very likely when the nose becomes moist with perspiration. Helmet and face mask connections for such apparatus are now abandoned, as they provide a dead space for CO_2 accumulation and are difficult to make so as to fit tightly on the wearer's face.

7. The apparatus must be constructed with a view to the comfort of the wearer ; the weight should not be excessive

[1] Second Report of Mine Rescue Apparatus Research Committee, p. 32.

and it should be distributed satisfactorily when the apparatus is being worn.

8. The oxygen supply should be adequate in quantity and in quality. The amount of oxygen in reserve is indicated by the pressure-gauge and the quality of the oxygen is found by periodical analyses. It must not contain more than 2 per cent of impurities, mainly nitrogen. The reason for this is that such impurities accumulate in the breathing bag throughout the work, even if the bag be filled with oxygen at the start. It is perhaps not necessary to repeat here that pure oxygen can be breathed for hours, perhaps for days, without any ill effects. Oxygen made by electrolysis of aqueous solutions or the like, generally contains a trace of hydrogen, from 0·02 to 2 per cent. At the Pittsburg Laboratory, U.S.A. Bureau of Mines, it was found that "a little more than 1 per cent of hydrogen in certain apparatus which was used to the limiting capacity for oxygen supply, caused the circulatory system of the apparatus to become charged with as much as 23 per cent hydrogen at the end of a two-hours' continuous use." Such a mixture of hydrogen and oxygen would be violently explosive, if ignited. The oxygen supply should therefore be examined for its hydrogen content, especially if it is electrolytic oxygen.

Types of Breathing Apparatus. There are three main types of breathing apparatus for rescue work: (1) smoke helmets, (2) compressed-oxygen apparatus, (3) liquid-air apparatus. A fourth type, the *Pneumatogen*, in which oxygen is generated by the action of the exhaled breath on sodium-potassium-peroxide, $NaKO_3$, has been devised and occasionally used on the Continent. The theory of this process is excellent, as the $NaKO_3$, on being attacked by the CO_2 and H_2O of the breath, gives off oxygen in the proportions indicated by the equation—

$$NaKO_3 + \underbrace{CO_2}_{\text{1 volume}} [+ H_2O] = NaKCO_3 + \underbrace{O_2}_{\text{1 volume}} [+ H_2O].$$

The CO_2, it will be seen, is absorbed at the same time. In practice, however, the apparatus has not yet proved successful

because of the development of excessive heat and of serious resistance to breathing, especially during periods of hard work. The small weight of the apparatus is a great advantage, but the above objections have been too serious to allow of the use of the apparatus in mines, and it is not an officially approved type.

All breathing apparatus for mine rescue work must be of an officially approved type. (See Rescue Regulations, 30th July, 1920.)

Smoke Helmets. These are not self-contained breathing apparatus, as the wearer depends upon a supply of fresh air sent to the helmet, which envelops his head, through a length of flexible tubing from a set of double-acting bellows or from an air pump or blower working in fresh air in each instance. Such apparatus are of great service in fighting fires in the mine, or elsewhere, provided that the fresh air supply is not more than 60 or 70 yards away. Compressed air may be sent through the tubing to the wearer.

Smoke helmets are simple in construction, protect the head of the wearer, and are cooler and far less cumbersome than ordinary self-contained breathing apparatus. Indeed, in many ways they are far more efficient, but they are practically useless in investigating a mine after an extensive explosion.

Fig. 39 shows the nature of the apparatus and connections, a waist belt being provided to take the weight off the head. The hose is about 1 in. internal diameter and strengthened and protected so as not to be damaged by wear, knocks or kinking. According to Dr. Haldane, a man requires about 6 cub. ft. of fresh air per minute when wearing a smoke helmet in a warm atmosphere.

The helmet may be provided with a blow-off valve through which the exhaled breath and extra air escape or the air and breath may escape from the bottom of the helmet, passing downwards under a flap-piece attachment of flexible leather, which is tucked under the wearer's coat. The " window " of the helmet is of clear mica.

The main objections to smoke helmets are: (1) vulnerability of the flexible hose, (2) danger of wearer being entrapped

by a fall as he must enter and return by the same way, (3) the restrictions to the wearer's movements, caused by the hose, (4) the necessity for keeping the hose out of the way of tubs and traffic, e.g. building a gob fire stopping, (5) inability of the wearer to retire rapidly, due to danger of hose becoming caught in centre props or other projections, (6) the hissing

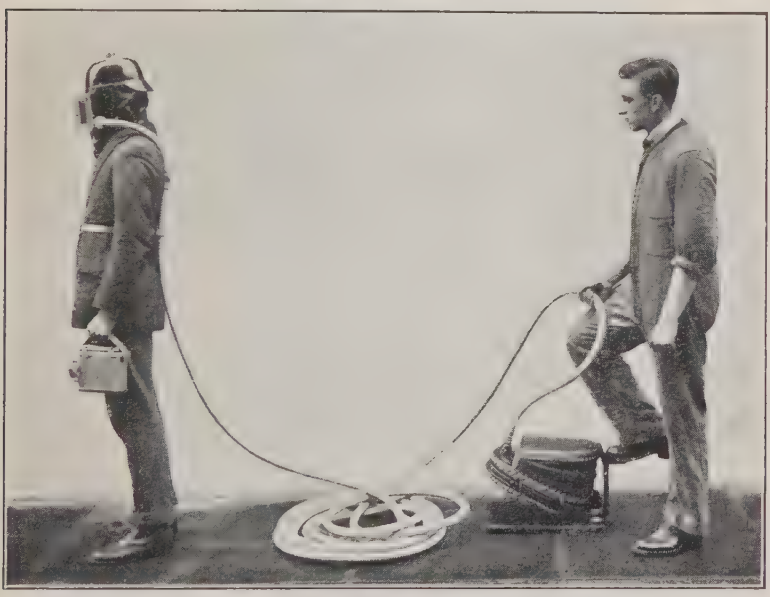


FIG. 39. SMOKE HELMET AND HOSE

noise of air entering the helmet, (7) the vision is limited, and (8) two persons are required.

Equalizers. To overcome objections (6), (7), and (8) above, Drs. Haldane and Briggs have devised apparatus in which the feed is through hose as usual, but in which there is a reservoir or bag in the breathing circuit and a mouthpiece with exhaling valve is substituted for the helmet. There is also an inhaling valve, in the supply pipe near the mouthpiece, which closes when the wearer exhales but opens on inhaling. The air is drawn through the hose by the action of inspiration, the bag acting as a cushion or reservoir; consequently, there is now

no need for a man at the bellows end, nor, of course, for any bellows or blower.

FIG. 40

Fig. 40 shows the *Meco-Briggs Equalizer Apparatus*, which operates in the manner outlined above. The bag carried on the back of the wearer is of "balloon" fabric, mounted on

strips of steel, which are bent round the sharp upper angle of the bag and thus form a frame which tends to keep the bag distended. Their action is further assisted by a coiled spring inside the bag. When the wearer exhales, the bag, which had been partially flattened during the last inspiration, recovers itself, and in so doing draws air through the hose. On the next breath, air is taken both from the bag and the pipe. By this means, a nearly steady flow of air is maintained in the pipe or hose. This requires far less work on the part of the lungs than if they had to maintain a pulsating flow ; and the bag also provides a reservoir for a deep breath. Saliva discharges through a " spear " exhaling valve protected by a metal guard. The *Antipoys Apparatus* designed by Dr. Haldane is similar in construction.

Smoke helmets may be fitted with telephone apparatus, which enables the wearer to communicate with the bellows man. This is no small advantage.

Compressed-oxygen Breathing Apparatus. The two best-known modern British types are the Proto and Briggs' improved Meco apparatus.

The Proto Apparatus is illustrated in Figs. 41, 42, and 43. Figs. 41 and 42 show back and front views of the apparatus ; the man is wearing goggles and nose clip. Fig. 43 is a flow diagram which explains more clearly the working of the apparatus. It may be stated here that the Proto apparatus is essentially an improved Fleuss apparatus, Mr. H. A. Fleuss being one of the pioneers in designing self-contained breathing apparatus.

The cylinder B (Fig. 43) contains 10 cub. ft. (at N.T.P.) of oxygen, under a pressure of 120 atmospheres, i.e. 1,800 lb. per sq. in. The oxygen is admitted to the breathing bag D at N, via pipe F and the reducing valve[1] C, which allows a flow of 2 litres per minute. H is the main valve, and is opened first of all. Since 10 cub. ft. is equivalent to 283 litres,

[1] A reducing-valve is a valve which supplies oxygen (or other gas) at a constant rate no matter how the pressure of oxygen in the cylinder may fall.

the apparatus will normally last about 140 minutes or, say, 2 hours. The by-pass valve *I* cuts out the reducing valve, but is used only in cases of emergency, when the normal oxygen flow is faulty or insufficient. The amount of oxygen remaining in the cylinder is indicated by the pressure-gauge *P*,

FIG. 41. PROTO APPARATUS
BACK VIEW

FIG. 42. PROTO APPARATUS
FRONT VIEW

which communicates with the cylinder via *W* and *V*. If the normal supply of 2 litres per minute is excessive, the breathing bag *D* becomes unduly distended, but discomfort may be avoided by opening the relief valve *K*. The bag is made of rubber, but is carried in casing of stout sail-cloth for protection. It is divided down the middle with a partition, which passes almost to the bottom, and in the bottom is placed the absorbent

for the CO_2 of the breath, the absorbent being either sticks of caustic soda (NaOH) or coke treated with caustic soda. Two valves are provided, one at *S* the other at *T*; *S* opening

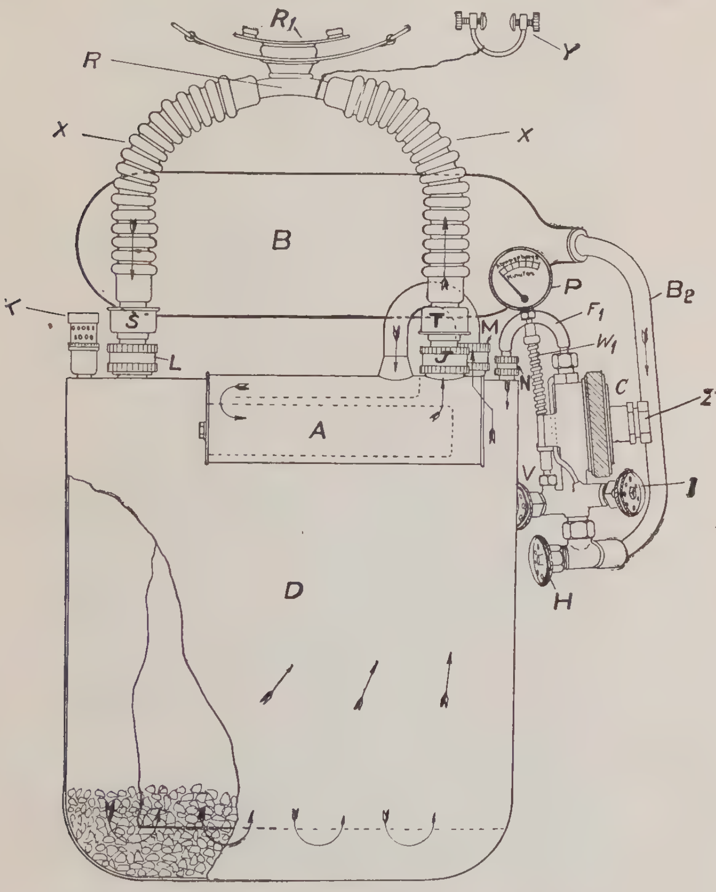


FIG. 43. PROTO APPARATUS FLOW DIAGRAM

and *T* closing on exhalation, and *S* closing and *T* opening on inhalation. The valves are mica discs controlled by light springs. The exhaled breath passes from the rubber mouthpiece *R* (shaped to fit between the lips and the gums), through

the flexible tube X and valve S, into the back portion of the breathing bag; then through the caustic soda, where the

FIG. 44. MECO APPARATUS. FRONT VIEW

CO_2 is removed, and finally through the cooler A via M where it joins the oxygen supply and passes to the wearer via J and T. The cooler consists of a number of thin sealed metal tubes about 6 in. long and $1\frac{1}{4}$ in. diameter, containing

calcium chloride, and carried in a special section of the breathing bag, as indicated. Calcium chloride, $CaCl_2 . 6H_2O$,

FIG. 45. MECO APPARATUS. BACK VIEW

melts at 84° F., and in doing so absorbs a large quantity of heat; by this means the heat developed by the caustic soda in absorbing CO_2 is neutralized to a great degree, and the discomfort of the wearer considerably reduced. *Y* is the screw nose-clip.

It will be seen that the circulation of the air in the apparatus depends entirely upon the natural movements of breathing. The weight of the apparatus is 37 lb.

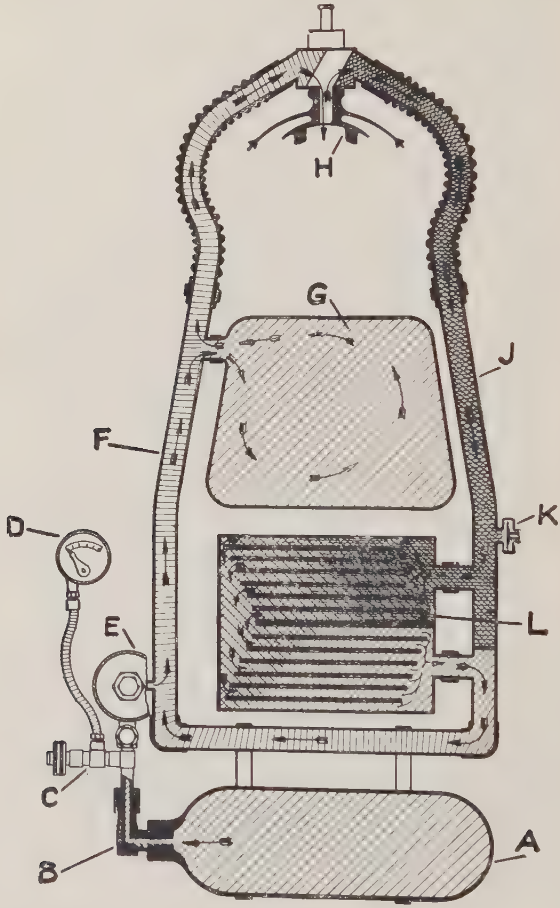


FIG. 46. FLOW DIAGRAM OF MECO APPARATUS

The Meco[1] Apparatus (as improved by Prof. Briggs) is also one of the compressed-oxygen type, but it differs from the

[1] Both the Proto and the Meco Apparatus are now made by Siebe Gorman & Co., London.

Proto in that the breathing bag is carried on the back of the wearer above the purifier, the latter being contained in a separate compartment. Figs. 44 and 45 give the general appearance of the Meco apparatus ; Fig. 46 is a flow diagram.

The flexible tube connections to the mouthpiece pass directly over the wearer's shoulders, and communicate one with the purifier *L*, the other with the breathing bag *G* and oxygen cylinder *A*, via a reducing-valve *E*. *D* is the pressure gauge. The flow of the gases will be clear from Fig. 46.

There is a by-pass emergency valve in the casing of the reducing valve. If the reducing valve becomes choked or fails from any cause, the emergency by-pass valve can be opened at once by pressure of the thumb. The breathing bag has a capacity of 5 litres, and is wedge-shaped. It is made of canvas coated with rubber inside and outside, and protected by a sheet-iron cover. The mouthpiece is fitted with mica valves $1\frac{1}{4}$ in. diameter, contained in inclined cages ; it also carries a saliva trap fitted with an india-rubber non-return valve through which the saliva may be expelled by pulling down the valve spindle. *K* is a relief valve, which opens automatically when the pressure inside the apparatus exceeds 4 in. water gauge ; it is fitted on the exhalation tube just above the purifier.

The original Meco apparatus worked on the injector principle mentioned below, but this has now been abandoned for some years.

Other forms of compressed oxygen apparatus are the Weg (W. E. Garforth), the Gibbs (U.S.A.), the Paul (U.S.A.), the Draeger (Germany) and the Tissot (France). Each of these has some minor distinctive features. Thus, in the Weg, the Gibbs, and the Paul apparatus, the supply of oxygen is automatically regulated by variations in the depth and frequency of the breathing.

In the **Draeger**, attempts were made to encourage the flow of air, etc., through the apparatus, by fashioning the oxygen inlet from the cylinder into an injector. By this device, inhaling and exhaling valves were largely rendered unnecessary

though useful when a helmet enclosing the head and face was worn, as in the older apparatus. The main objection to the injector is that it is liable to cause a negative pressure behind it, and thus cause an inflow from the outer atmosphere should the apparatus be leaky. Other objections are (1) that if it becomes imperfect, there is risk of breathing exhaled breath over and over again, (2) that it is easily choked, and (3) that if the mouthpiece should be temporarily removed by accident in a poisonous atmosphere, the apparatus will suck in some of the poisonous air. In the modern Draeger apparatus the injector principle has been abandoned.

In the **Tissot** apparatus, a *solution* of caustic potash in water is used to remove the CO_2, and there is a variable reducing valve and flow gauge by which the wearer can adjust the oxygen supply to the points marked "Rest," "Marching," "Work," or "Aid," in accordance with what he is doing.

Liquid-air Apparatus. Liquid-air apparatus is in essentials similar to compressed-oxygen apparatus, but there is no reducing valve. Liquid air contains as a rule more than 60 per cent of oxygen, and seldom less than 45 per cent. Moreover, when it is stored (in special vacuum flasks unstoppered), the nitrogen evaporates more quickly than does the oxygen, so that the liquid air actually used contains generally 70 per cent of oxygen or more. It is, therefore, more nearly liquid oxygen than liquid air.

The following *physical data* are taken from the Third Report of the Mine Rescue Apparatus Research Committee (1924): "Liquid nitrogen is colourless; it has a density of 0·81 (water = 1), and at normal pressure it boils at $-196°$ C. Liquid oxygen is a transparent blue; its density is 1·13 and its boiling point $-184°$ C. The temperature of the mixture in the storage flasks is usually between $-186°$ C. and $-190°$ C. The presence of small proportions of finely-disseminated ice or solid CO_2 (indicating imperfect purification and drying of the air prior to liquefaction) can be recognized by the cloudy appearance they give to the liquid."

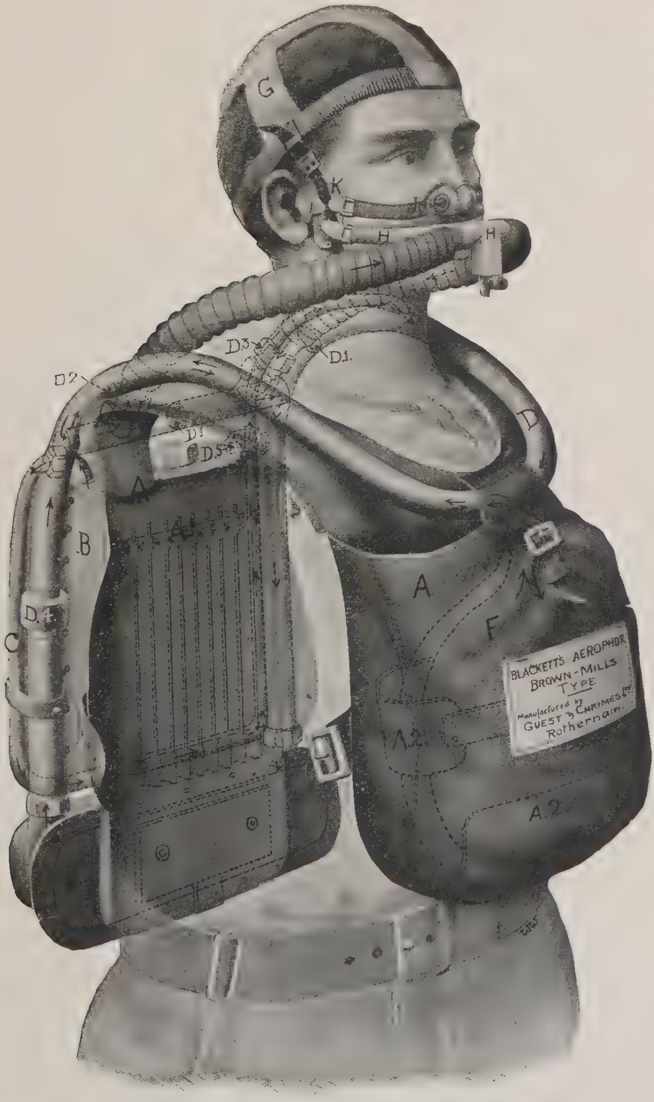


FIG. 47
BLACKETT'S AEROPHOR. BROWN-MILLS TYPE

Liquid air (60 per cent oxygen) yields about 780 times its volume of gas at 60° F. and 30″ mercury.
Liquid air (100 per cent oxygen) yields about 840 times its volume of gas at 60° F. and 30″ mercury.
1 lb. of liquid air (60 per cent oxygen) yields about 356 litres at 60° F. and 30″ mercury.
1 lb. of liquid air (100 per cent oxygen) yields about 334 litres at 60° F. and 30″ mercury.

Liquid air is made by highly compressing and cooling ordinary air after freeing it from dust, water, and CO_2. The atmospheric air is first compressed to 50 to 100 atmospheres, and then part of this highly-compressed air is allowed to expand through a jet into a vessel containing coils, in which the rest of the compressed air is circulating. The absorption of heat by the expanding air round the coils cools the air inside, until, under its high pressure, it liquefies. Oxygen liquefies more easily than does nitrogen, hence, the liquid air contains over 50 per cent of oxygen as a rule. If the nitrogen be allowed to boil off, a stage is reached when the gases coming off contain over 99 per cent of oxygen, and in this manner much of the compressed oxygen of commerce is obtained.

The Aerophor. This apparatus is a development of the *Aerolith*, in which no attempt was made to use the purified exhaled breath, the expired air either escaping or being breathed over again (see First Report of the Royal Commission on Mines, 1907). A modern form of the Aerophor (Blackett's Patent—Brown-Mills type) is shown in Fig. 47.

About 5½ lb. of liquid air is weighed into the pack B, the latter being suspended from a spring balance. In B the liquid air is absorbed by calcined asbestos wool B_1 (Fig. 48), which is held in a perforated container B_2. B_2 is enclosed in a second chamber B_4, the space between, i.e. B_3, constituting the evaporating chamber. The evaporated air passes from the pack at B_{12} after traversing the insulating space B_5. B_{11} is the filling tube. The object of the numerous enclosures,

one within the other, is to reduce the rate of evaporation, and to protect the wearer's back from the cold. To ensure thorough protection there is a strong outer casing with a leather cover. Pieces of thick felt are placed between the back of the wearer and the pack.

The air leaving the pack passes into the circulating tubes

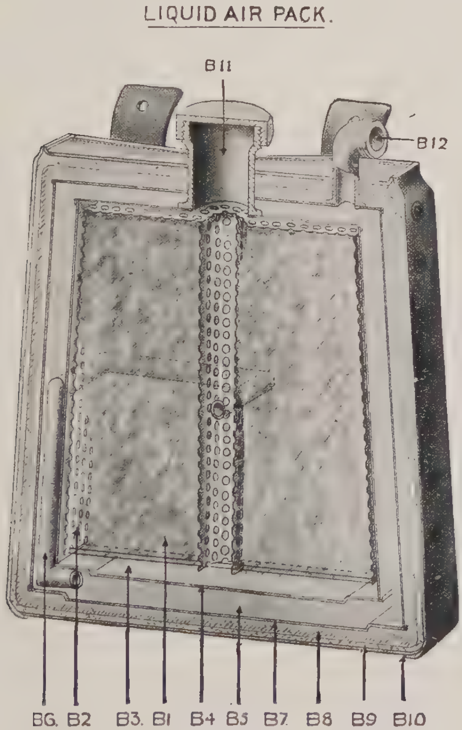


FIG. 48

D and into the breathing bag *F*, or directly to the mouthpiece *H* (Fig. 47). The exhaled breath passes through the exhaling valve D_3 to the purifier *E*, which lies below the pack and is insulated from it by thick felt. The gases leaving the purifier pass to the breathing bag, where they join the fresh supply of air from the pack, the mixture then being breathed again.

Any excess air—and there is a large excess at the start—escapes through the relief valve D_5, which is placed in the exhaled breath portion of the circuit. Consequently, the purifier is not required and does not come into action until D_5 closes, the air supply then ceasing to be excessive. Fig. 49 is a flow diagram of the apparatus. The weight of the apparatus when fully charged is about 30 lb., and its lightness and the coolness of the air supply are its great advantages. A minor disadvantage of this apparatus is the necessity of using it immediately it is charged, as the liquid air cannot be "kept." Another is the expense and trouble of the manufacture, storage, and transport of liquid air. The rate of evaporation of liquid air in special large vacuum flasks holding 50 lb. is about 3½ lb. per day when stationary; and 6 lb. per day in transport, but the latter figure varies somewhat with the "smoothness" of the journey.

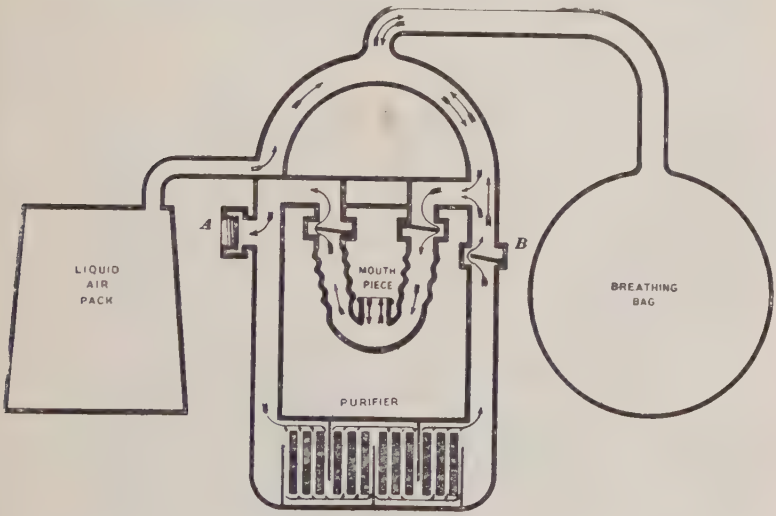
Gas Masks or Respirators. These apparatus depend upon the use of an absorbent (prepared charcoal for ordinary fumes, and "hopcalite" for fumes containing CO), through which the inspired air is drawn. Charcoal is capable of absorbing large volumes of easily liquefied gases, but is useless for absorbing carbon monoxide, the main danger in poisonous mine atmospheres. A form of gas mask,[1] however, has been devised in which CO in the air is converted to CO_2 by means of a specially prepared mixture of 27 parts of manganese dioxide, MnO_2, to 1 part of copper oxide, CuO, the mixture being known as "hopcalite."

These gas masks cannot be employed successfully in air in which the oxygen percentage is less than 10; but if used only where a safety-lamp will burn, i.e. where there is present at least 17 per cent of oxygen, they have much to recommend them.

The hopcalite is contained in a canister 6½ in. × 2½ in. × 7¼ in. long, and is well protected from moisture by layers of fused calcium chloride above and below. The air is drawn

[1] *Trans. Inst. Min. Eng.*, Vol. LXVIII, p. 278; Vol. LXIX, p. 19; Vol. LXIX, p. 207.

into the bottom of the canister through a disc check valve normally held closed by a light spring ; it then passes through the calcium chloride (and other drying media) to the hopcalite, where the CO is oxidized to CO_2, then through the upper layer of calcium chloride and finally through a second disc check-valve backed by a light spring, before passing to the mask which encloses the mouth completely. The exhaled



FLOW DIAGRAM.

FIG. 49

air passes out through a special valve as indicated. (See Fig. 50.)

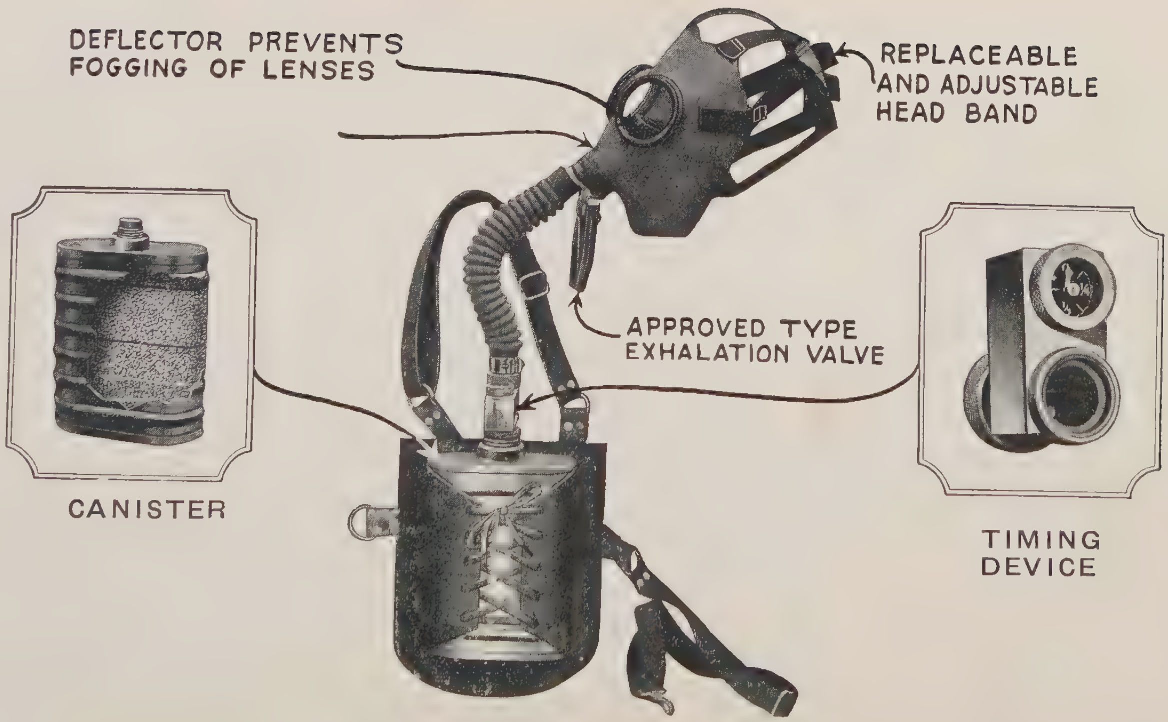
The conclusions reached by **Ritson** and **Hartley**[1] on testing these hopcalite gas masks, are that—

1. The canister provides complete protection against CO up to at least 1 per cent.

2. The canister does not provide protection against CO_2 (or oxygen shortage, i.e. below 10 per cent).

3. The hopcalite, which is only effective when dry, is satisfactorily protected against moisture.

[1] *Trans. Inst. Min. Eng.*, Vol. LXIX, p. 207.



Weight of Mask as shown only 5¾ lbs.

Fig. 50

4. The resistance to breathing when air is passing at the rate of 80 litres a minute does not exceed 6 in. of water gauge.

5. The temperature of the inspired air rises to a high limit when a combination of very moist air with 1 per cent of CO is breathed. When 0·5 per cent of CO is present the temperature, though still high, is breathable.

Improved respirators of this type will probably be of great service in dealing with gob fires and even in recovery and rescue work after mine explosions. A flame safety-lamp must be used along with the respirator and a canary or mouse in cage (see page 56) provides a useful indication of when to don the apparatus.

CHAPTER XVII

RESCUE STATIONS AND RESCUE BRIGADES

Rescue Men. It is compulsory at all collieries, except those employing only a few hands underground, to make suitable provision in the matter of rescue men, breathing apparatus, and ambulance rooms, in case of an explosion or other similar emergency. One of two schemes must be adopted, namely, either (*a*) the 1913 scheme, in which a proportion[1] (about 1 to 2 per cent) of the men employed underground are trained in the use of breathing apparatus and in rescue work generally, a number of suits of breathing apparatus being kept at the colliery or at a central rescue station, or (*b*) the 1914 scheme, in which fewer men[2] (about 0·2 to 1·0 per cent of the underground employees) are trained, but there is maintained a central rescue corps in constant residence at a central rescue station. In the 1914 scheme there must be kept at each mine either 2 suits of self-contained breathing apparatus or 2 smoke helmets or one of each. There are 6 to 8 central rescue stations in each of the main coalfields of Great Britain.

In the 1913 scheme, each colliery has its own rescue brigades, a brigade consisting of from 5 to 7 men: in the 1914 scheme, the trained men together with men from other collieries form the rescue brigades. Under the 1913 scheme the brigades may be trained either at the colliery or at the central rescue station. If the colliery is too distant[2] from the central rescue station, the colliery has to be its own training ground, and has then to keep several suits of self-contained breathing apparatus. Not less than 6 suits is now recommended for such collieries.

Central Rescue Stations. Fig. 51 shows a plan view of the Wakefield (Yorkshire) Rescue Station, where the Proto

[1] The exact proportions are at present (1926) under revision.
[2] The Rescue Regulations Committee Report, 1926, suggests a maximum distance of 15 miles.

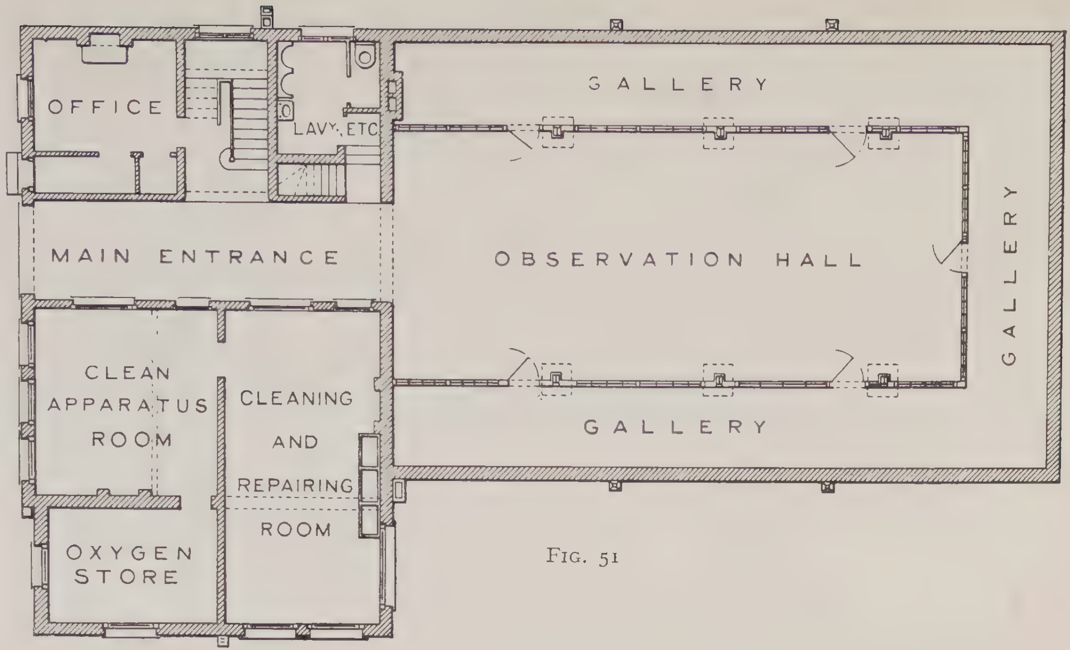

GALLERY
OFFICE
LAVY. ETC
MAIN ENTRANCE
OBSERVATION HALL
GALLERY
CLEAN
APPARATUS
ROOM
CLEANING
AND
REPAIRING
ROOM
GALLERY
OXYGEN
STORE

FIG. 51

apparatus is in use. On the right of the entrance are the Apparatus Rooms, the Oxygen Store-room, and the Cleaning and Repairing Room. On the left of the entrance are the office and the lavatory accommodation. The entrance leads direct into the observation hall, round which is the gallery. In the galleries irrespirable atmospheres are produced, and men undergo training with the breathing apparatus, as stated in C.M. Regs. Swing doors are provided, as indicated, to allow ready access to fresh air in case of emergency, and the galleries are provided with ventilation doors, air-crossings, timber, tubs, rails, etc. Sometimes the galleries communicate through a small shaft or staple pit, with underground roadways equipped in the same manner as mine roadways.

At all central stations a motor-car has to be maintained in readiness, and a telephone is, of course, imperative. A fire-engine car is also maintained.

Men for Rescue Work. The selection of the men for training for rescue work and recovery work is not easy. Such men should be not only physically fit, but also above the average intelligence and of strong character and sober habits. Moreover, it is very desirable that the offer to serve should come from the man himself. It is thought that men should be excluded who are not between 22 and 40 years old, or who have not had at least two years' experience in the mine. The men should be examined medically at the start and then every year, for physical fitness.

Ergometer. In this examination *Martin's Ergometer*[1] (Fig. 52) is useful. It consists of a bicycle in which both wheels are raised from the ground, and as the front wheel is not required it is discarded, the front forks being supported by a strong, rigid post. The back wheel is made far heavier than that of an ordinary bicycle wheel and round the rim, which has no tyre, is passed a linen brake-band, the ends of which are connected by cords to spring balances. The cords can be adjusted and the brake resistance varied accordingly.

[1] Appendix II to Second Report of Mine Rescue Apparatus Research Committee, 1920.

The back wheel is about 21 in. diameter, i.e. 66 in. or $5\frac{1}{2}$ ft. circumference, and the gearing to the pedals is $3\frac{1}{4}$ to 1, so

FIG. 52

that for 1 revolution of the pedals a point on the wheel's circumference travels $5\frac{1}{2} \times 3\frac{1}{4} = 18$ ft. If the speed of the

pedals be 55 r.p.m., the speed of the back wheel is $55 \times 18 = 990$ ft. per minute; and if the difference of the tensions registered by the spring balances is, say, $7 - 3 = 4$ lb., the work done per minute is $990 \times 4 = 3{,}960$ ft. lb. It is convenient to have a pendulum in sight of the "subject," the pendulum being adjusted to make 56 swings a minute and the subject instructed to pedal so as to make 56 revs. of the pedals per minute; since at this rate of pedalling the difference of

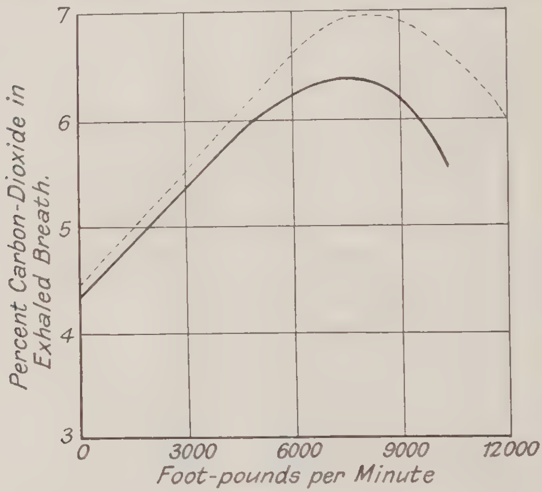


FIG. 53

the spring-balance reading multiplied by 1,000, gives directly the foot-pounds of work done per minute. The rate of work can be governed by slackening or tightening the cords which connect the band brake with the spring balances. The pulse and condition of breathing of the man are noted before the test and at the end, and at 5-minute intervals for 20 minutes, and finally an hour later. Recovery to normal breathing and pulse rate should be easy and rapid. Moreover, the percentage of carbon dioxide in the exhaled breath during work should at first rise gradually as the load on the brake increases, and not begin to fall until the rate of work exceeds

6,000 ft.-lb. per minute. Indeed, the greater the crest load the better. Fig. 53[1] shows the general form of the results obtained, expressed graphically.

A sample of the exhaled breath is obtained by causing the subject to breathe into a Douglas bag, which is a large rubber-lined, bellows-shaped bag, which acts as a receiver or reservoir, from which samples may be taken. The subject is fitted with an ordinary rescue apparatus mouthpiece and connections, and noseclip, and can be allowed to inhale either oxygen or air.

It has been found that sedentary workers produce a low percentage, less than 5, of CO_2 in the breath when breathing air, and have a small crest-load, perhaps as low as 3,000 ft.-lb. per minute. On breathing oxygen the values improve somewhat, but do not approach those of a physically-fit subject, who, in contrast, derives but little benefit from breathing pure oxygen instead of air.

The training which rescue brigades and central rescue corps have to undergo is prescribed in the present Regulations, and is dealt with in *Mining Law and Mine Management*, in this series.

[1] Appendix II to the Second Report of the Mine Rescue Apparatus Research Committee.

CHAPTER XVIII

RESCUE AND RECOVERY WORK

Procedure After Explosions. The procedure laid down in the Third Schedule to the 1920 General Regulations is as follows—

Uniform Code of Rules for the Conduct and Guidance of Persons Employed in Rescue Work

Manager or Principal Official for the Time Being at the Surface of the Mine. (1) On receiving information of any occurrence likely to require the service of a rescue corps or brigade, the following steps shall be taken by the manager, or, in his absence, by the principal official present at the surface—

(*a*) Telephone to the central rescue station. Inform the instructor of the character of the occurrence. State whether assistance will be needed from rescue brigades other than the permanent station corps or the brigades attached to the mine.

(*b*) Summon the trained men attached to the mine.

(*c*) Telephone for medical assistance.

(*d*) Telephone to the inspector of mines and the local offices of the Miners' Union, and the Firemen's, Examiners', or Deputies' Association.

(*e*) If necessary, communicate with the police station.

(2) No person shall be allowed to enter the mine or the part of the mine which is unsafe for the purpose of engaging in rescue operations unless authorized by the manager, or, in his absence, by the principal official of the mine present at the surface ; and, during the progress of such operations, a person or persons shall be stationed at the entrance of the mine, and required to keep a written record of all persons entering and leaving the mine. Only men trained with the apparatus shall be permitted to enter the mine for the purpose of using breathing apparatus.

(3) Prior to sending a brigade underground clear instructions shall be given to the leader of the brigade as to where it shall go and what it shall attempt. Unless the leader is personally thoroughly familiar with the roadways in question, the route shall be marked on a tracing, which the leader shall take with him into the mine.

(4) A qualified medical man shall be in attendance at the mine wherever rescue parties are at work, unless in the opinion of the manager and of the inspector of mines and miners' representative (if present) that course is unnecessary.

The doctor, when present, shall examine every man engaged in rescue work before permitting him to go underground for a second spell of that work.

(5) As soon as possible a base or bases shall be established in fresh air, but as near to the irrespirable zone or zones as safety permits. Each such base shall, if possible, be connected by telephone to the surface or to the shaft bottom. Whenever men are at work beyond the base there shall be stationed at the base as soon as possible the

following : (*a*) Two men, of whom at least one should understand rescue appliances and first aid ; (*b*) a spare brigade with rescue apparatus and ready for immediate service ; (*c*) one or more oxygen revivers, stretchers and birds.

Captain or Leader of a Rescue Brigade. (6) The leader shall not permit the brigade to go underground until he has received clear instructions from the manager or from the person acting on the manager's behalf ; and, unless the leader knows the route thoroughly, he shall take underground a plan on which the route is clearly marked.

(7) The leader shall not engage in manual work. He shall give his attention solely to directing the brigade and to maintaining its safety. He shall examine the roof and supports during the journey inbye, and, if there is any likelihood of a fall, he shall not proceed until the brigade has made the place secure. He shall not take the brigade through any passage less than 2 ft. high and 3 ft. wide, except in a case of urgent necessity.

(8) When the atmosphere is clear, the leader shall, when passing the junction of two or more roads, clearly indicate the route by means of arrow marks in chalk. When the atmosphere is thick with smoke the leader shall see that a life-line is led in from fresh air, and shall not allow any member of the brigade to move out of reach of that line ; or, if that course is impracticable, he shall not proceed until every road branching from the route is fenced across the opening.

(9) Before proceeding underground the leader shall test, or witness the testing of, every rescue apparatus of the brigade. He shall check the equipment of his party, and, immediately before entering irrespirable air, make sure that every apparatus is working properly.

(10) When using rescue apparatus the leader (who shall carry a watch) shall read the pressure of the compressed oxygen every 20 minutes, or thereabouts, and shall commence the return journey in ample time. In travelling he shall adapt the rate to that of the slowest member.

Members of Rescue Brigades. (11) Members of brigades shall, in general, use the prescribed signals in communicating to one another.

(12) In travelling with rescue apparatus, each member of the brigade shall keep the place given him when numbering off. If the pace is too quick, or if distress is felt for any reason, the member shall at once sound the distress signal.

(13) No person shall commence a second or subsequent spell of work in bad air without being examined and passed by a doctor, if present, or by the rescue station instructor or other competent person if the doctor be not present.

These regulations form an excellent guide to the general procedure after an explosion, but a few additional notes are desirable.

Dr. Haldane has well summarized the usual conditions prevailing after an explosion.[1] A gas explosion or a blown-out shot has probably caused a coal-dust explosion, which has

[1] " Possibilities of Rescue Work in Connection with Mine Explosions and Fires," by J. S. Haldane, *Trans. Inst. Min. Eng.*, Vol. XXXIX, Part 3.

travelled along all dusty roads, (unless a large excess of stone-dust has been employed) more especially along the main haulage roads, which are generally intakes. The explosion will, therefore, probably have wrecked these roads and perhaps also the winding appliances of the downcast shaft. Air-crossings may have been destroyed, doors blown out, roof supports dislodged and large falls consequently blocking the road. The upcast shaft, if not used for coal winding, is often undamaged ; but if used for coal winding it will probably have suffered the same fate as the downcast. The fan may be thrown out of action, and most of the ventilation, in any case, will be short-circuited through damaged doors and air-crossings. The air on the roads along which the explosion has travelled may contain 2 or 3 per cent of CO, and this air may be taken round the workings or straight to the shaft, depending upon which direction the air happens to flow at the moment. Finally, fires may have been caused in the various sections of the mine traversed by the explosion.

The non-dusty roads of the mine and the coal face, as a rule, are not charged with afterdamp until some time after the explosion, and it is probably best for the men in these districts not to attempt hasty escape but to remain where they are and build temporary stoppings in order to shut out most of the foul air. They will certainly enclose enough good air to last for several hours, and with a small leakage, perhaps for several days. They may, on the other hand, find it convenient to go to a compressed-air supply near by, but in any case they should make attempts to short-circuit the air which may travel to them, as it probably contains CO. The short-circuiting can often be done by opening doors outbye. The men should *not* try to escape along roads that the explosion has travelled ; such a procedure is almost invariably fatal.

The Work of Rescue. To rescue these men it is necessary as a rule to re-establish the ventilation, i.e. to take them a supply of fresh air, and this is generally the main work of the rescue teams. Occasionally it is necessary to bring a few men out through a poisonous atmosphere by supplying

them with some modified breathing apparatus, but the leading in of a fresh air supply is the usual procedure. Before the arrival of the rescue teams, attention should be paid to the following—

1. Keep all air compressors working, as some of the men in the mine may be depending upon the compressed air there.

2. Inquire by telephone (if possible) concerning the state of affairs in the mine.

3. To avoid accidents, cut off the electric current supply to the mine.

4. If all the winding appliances are out of order, and incapable of speedy repair, erect temporary winding arrangements.

5. Establish a surface head-quarters.

On arrival of the rescue men, a bird in a cage and a sampling tube (previously evacuated of all air) and a safety-lamp, should be taken down the shaft by a man or two wearing breathing apparatus. If the lamp is extinguished, there is either (1) a shortage of oxygen, or (2) an explosive atmosphere; if the bird shows signs of poisoning, the presence of more than 0·1 per cent of CO may be inferred. The sample of the air should be analysed at once, in order to show the state of affairs. The air in both downcast and upcast shafts should be tested in this way, and the state of the ventilation noted—whether, for instance, it is brisk or stagnant, whether normal or reversed, whether cooler or hotter than usual, and so forth.

Brigade Operations. A brigade or team of about 6 men, wearing breathing apparatus, in position if necessary, may then descend one of the shafts and make a preliminary investigation of the mine to determine the actual conditions underground. They proceed to test the air for CH_4 and for oxygen shortage, by using a flame safety-lamp, and for CO by means of a bird. Samples of air are also collected for chemical analysis. The nature and extent of the disaster are estimated, and the condition of the roads and direction of

the ventilation are noted. On the return of the team the captain reports on the state of affairs, and the manager and other officials, in consultation, decide upon a plan of campaign.

If only one district of the mine has been involved, the work is generally straightforward, but if the greater part of the mine has suffered, it becomes necessary to "recover" the mine in sections, one at a time, the others being closed off by temporary stoppings of timber, brattice, shale, bricks or the like, *faced with moist clay*. (See page 164.) A pipe may be built into each of the stoppings, so that samples of the atmosphere on the far side may be taken periodically.

Any coking of the coal on the mine timbers should be noted; this is generally most marked on the sides of the timber away from the source of the explosion, due to the backward pressure wave mentioned on page 52. Near the source there is usually little evidence of violence.

Recovering a District. The work of recovering a district consists in making the roadway safe and passable, and in carrying forward the ventilation by dividing the roadway with brattice or, better, by using air-tubes about 1 ft. diameter of sheet iron with a small fan or compressed air injector nozzle, e.g. the Korting Injector. When a cross-road between intake and return is reached, the air may be allowed to take the normal course through the cross-road, if the roads are in sufficiently good condition. As the "recovering" is pushed forward beyond the cross-road, however, recourse has again to be made to the air-tubes or bratticing.

Where survivors are found, and it is necessary to take them through a zone of poisonous atmosphere to rescue them, they are provided with some form of breathing apparatus until the poisonous region has been traversed.

If the rescue and recovery operations are likely to last several days, it is necessary to make adequate provision for the teams as regards (1) mess-room for the men, (2) sleeping-quarters, (3) room for any dead bodies, (4) large supply of oxygen or liquid air, (5) continuous attention by at least one qualified medical man.

Programme of Work. It is also necessary to draw up a programme for the work. A suitable arrangement is shown in the following table, six teams each of six men being employed. Each team has 4 hours on duty, then 8 hours rest. Meals are arranged so that a man does not have a meal within the 2 hours before he dons the apparatus. This has been found desirable from past experience.

TEAMS A, B, C, D, E, AND F

12 noon to 2 p.m.—
A at work, B at base, C, D, E, and F, resting, sleeping, etc.

2 p.m. to 4 p.m.—
B at work, C at base, D, E, F, and A, resting, sleeping, etc.

4 p.m. to 6 p.m.—
C at work, D at base, E, F, A, and B, resting, sleeping, etc.

6 p.m. to 8 p.m.—
D at work, E at base, F, A, B, and C, resting, sleeping, etc.

8 p.m. to 10 p.m.—
E at work, F at base, A, B, C, and D, resting, sleeping, etc.

10 p.m. to 12 night—
F at work, A at base, B, C, D, and E, resting, sleeping, etc.

12 night to 12 noon arranged similarly.

Fires. The composition of the return air will afford some indication of whether any mine fires have been started by the explosion. Any such fires are dangerous not only because they may spread, but also because they may ignite explosive mixtures of firedamp and air, and thus cause further explosions. The districts in which fires are found should therefore be explored at once, and the fire quenched and dug out if possible, or the district sealed off in the manner discussed on page 164. If there is a fire near the bottom of the downcast, its growth may be checked and loss of life avoided by **reversing the ventilation** by means of the arrangements provided at the surface for this emergency. But such complete reversal of the mine ventilation is a dangerous expedient and should only be undertaken after full deliberation. The main dangers are (1) the intake air towards which the men in the mine will

probably have been proceeding will become the return, (2) the (old) return becomes the intake, and a body of firedamp and air may therefore now be fed to the fire, (3) the ventilation doors between intakes and returns will open and cause much short-circuiting. If, however, it is known that the fire near the downcast bottom is the only one, it is undoubtedly best to reverse the ventilation at once; and the same procedure should be adopted if a fire breaks out on the screens, if there is any danger of the fumes going down the shaft. A fire at a surface engine house at New Moss Colliery in 1900 spread to the shafts and travelled down the downcast by inflaming the grease and oil on the winding and guide ropes.

CHAPTER XIX

INUNDATIONS

SERIOUS accidents involving the simultaneous loss of many lives at collieries fall into three main categories: (1) firedamp explosions, (2) coal-dust explosions, and (3) inundations. It remains only to treat of the third class, namely, inundations, or inrushes of large quantities of water into the mine. In recent years there have been two or three grave accidents from this source. At Redding Colliery in September, 1923, 40 lives were lost due to an inrush of water from the disused workings of a mine roughly 100 years old; and at Montague Colliery, Scotswood, near Newcastle-on-Tyne, in March, 1925, 38 lives were lost through a similar cause. It is necessary, therefore, to take all precautions against such occurrences.

Precautionary Measures. The precautions to be observed are: (1) The making of thorough inquiries regarding all old workings, (2) The inspection of all plans of previous workings. (3) The recording of the results of (1) and (2) on a special plan or on the working plan. (4) The issuing of instructions to the mine officials and workmen to report at once any unexpected or serious inflows of water. (5) The carrying out of the Coal Mines Act Regulations regarding the procedure to be adopted when approaching old works and when working under moss.

It will be convenient to state briefly, first, the regulations concerning workings under moss and the like.

Workings Under Moss or the Like. The Coal Mines Act Regulations of 30th July, 1920, state that where coal or other mineral is being worked (or roads driven) under moss, quicksand, oil, or the like, the following precautions must be taken:

1. "The nature and thickness both of the moss, quicksand, or other liquid matter, and of the strata lying between it, and the workings or roads shall be ascertained as accurately

as possible by boring at a sufficient number of points or otherwise."

2. "If the thickness of the intervening strata is found at any point to be less than 60 ft. or ten times the thickness of the seam worked, whichever is greater, no further work except work necessary for the preservation of the mine shall be carried on below ground except with the consent of the Secretary of State, and subject to such precautions as he may direct."

The same regulations also give details for forming a committee to advise the Secretary of State on any cases arising as above.

These regulations have been drawn up on account of a number of disasters which have occurred (mainly in Scotland) where mossy bog land, heavily charged with water, has broken through into the mine workings. They call for little comment.

Old Workings. With regard to information concerning old workings, there will probably be no official copy in the Mines Department records of the mine plan if the mine was abandoned before the Coal Mines Regulations Act of 1872. This Act made it compulsory to send to the authorities a plan of any mine subsequently abandoned, and the Coal Mines Act, 1911, stipulates that the plan shall indicate all essential details, e.g. pillars, headings, faults, dykes, surface features, dip and depth. The only way, therefore, to collect information of mines worked before 1870, is to make inquiries from mining engineers and others in the district, and to make copies of all old plans which are likely to prove of service. The forwarding to head-quarters, i.e. the Mines Department, of copies of all old plans, while not compulsory, ought to be regarded as a matter of duty by any who possess them. It is probable that if such plans had been accessible, some of the recent accidents would not have occurred.

For mines abandoned after the year 1872, the plans will probably be available at the Mines Department, and should be consulted where there is the least danger that the old workings may be approached in the operations in hand. The old workings are, of course, not necessarily full of water,

and if the mine be naturally dry they will more probably be full of blackdamp. But precautions are again necessary.

The information collected should then be recorded and the dangerous zones marked distinctly—on the working plan, for preference, lest they be overlooked. In transferring the bearings of old workings to a plan, allowance must be made for the change of magnetic meridian, unless the roads, etc. are plotted with reference to some surface features clearly shown on the old plan : and the accuracy of old plans must always be questioned until proved.

Instructions to Workmen. The issuing of instructions to underground workmen to report small inflows is of great

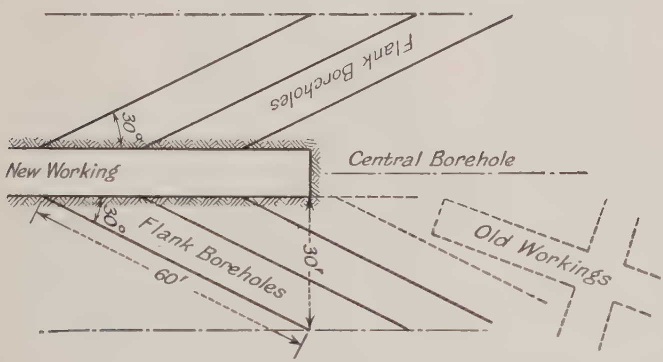


FIG. 54

importance, as it is usual for leakages to be observed for some hours or even days prior to an actual inrush. On receiving such reports, the manager should refer at once to the plans and records of the old works, etc., in order to see if there are likely to be serious consequences. It may in such circumstances be imperative to remove all the men from the mine immediately.

Safety Regulations, C.M.A., 1911. In Section 68 of the Coal Mines Act, 1911, it is laid down that when any working face has approached within 40 yd. of a place likely to contain an accumulation of water (or oil), a heading shall be driven not more than 8 ft. in width with boreholes on the flanks

at 5-yd. intervals or less, and a leading borehole at least 5 yd. in advance.

Fig. 54 shows the nature of such a heading approaching old workings : the necessity for side holes from the heading is clearly shown. Moreover, it is advisable to adopt these safety measures at about 60 or 70 yd. from the supposed accumulation of water, in case the old plans are inaccurate.

A more usual procedure than that indicated above is to stop the face 70 or 80 yd. from the old works, and bore a long hole until the old works are struck. There are several

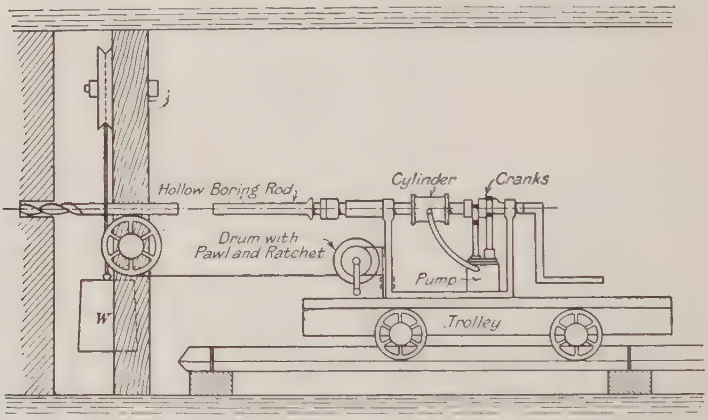


FIG. 55

machines for such work, the best known being the Burnside, described on the next page.

Hunter's Boring Machine. Fig. 55 shows in elevation Hunter's Boring Machine, which has been much used for this class of work. It consists of a drill with boring rods mounted in a frame on a trolley, which is held to the work by a weight and pulleys, as shown. The boring rods, about 1 in. diameter, are hollow, and made in 6 ft. lengths. The rod extension near the handle is cranked, and the small vertical connecting-pieces are used to work a pump which delivers water to the boring bit through the inside of the rods, thus cleaning out the hole and " lubricating " the bit.

The hole should be set off inclined upwards a little, to counteract the tendency of the rods to bore downwards, due to their weight. Long, dry wooden plugs should be kept in readiness to drive in when the water has been tapped, and both flame and electric safety-lamps should be used, with spares in the rear in case of emergency.

Holes 160 or 170 ft. long have been bored with this machine by two men in two shifts of 8 hours, i.e. 80 ft. per shift.

Burnside Boring Machine. In this machine (Fig. 56) provision is made for controlling the water when tapped. In the first place, a length of 3 ft. 3 in. of the hole is widened out, and of this the first 2 ft. 10 in. (i.e. up to *C*) is bored wider than the last 5 or 6 in. At *C* is placed a thick rubber washer. The drill, together with four special tapering wedges, is then inserted into the hole, the thick ends of the upper and lower wedges being placed against flange *D*, while the thick ends of the side wedges are pushed against the rubber washer at *C*. The upper and lower wedges are hammered in tightly, and the side wedges then drawn outwards towards *D* by their bolts *B* and the nuts *N*. This forces in the upper and lower wedges and compresses the rubber washer, thus effecting a sound joint and powerful grip on the walls of the hole. If desired, the joint can then be tested by a hand-pump and pressure gauge: there should be no serious leakage at 200 lb. per sq. in. pressure.

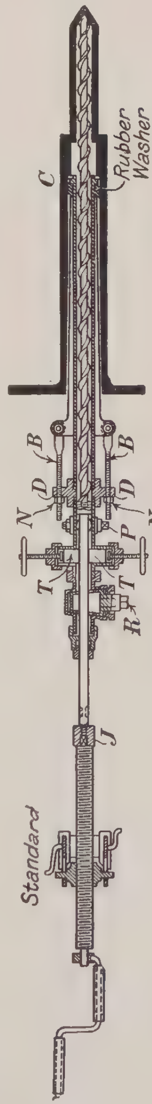


Fig. 56

The main boring may now be started, the rods being added at *J* as the necessity

arises. When water is struck, the flow may be arrested by means of the two pieces *I* (of stout rubber) which can be screwed up tightly against the rods. There is also a tap at *R* which is open during the boring, but may be closed once the rods have been withdrawn.

In some Burnside machines, water is circulated as in the Hunter machine.

Water Blast. For one or other reasons, it is sometimes decided to de-water or drain old workings by pumping. In these circumstances, after the pumping has proceeded for a while, there is not infrequently a sudden geyser effect, a quantity of the water being thrown forward with violence and a large amount of gas liberated. This phenomenon has been called a "water blast." It is due to the fact that a certain volume of gas has been enclosed in the cavities, in the coal, etc., by the water, and held under high pressure, if the head of water is great. On reducing the head by pumping, a point is reached when the gas pressure is sufficient to overcome the water pressure and does so with violence, causing a kind of geyser. The gases may be largely blackdamp, but firedamp may also be present in considerable amount, so that the usual precautions are necessary with regard to electric sparks, flames, etc.

APPENDIX I

Questions selected from those set by the Board of Mining Examinations for Certificates of Competency of Colliery Managers and Under-managers (First and Second Class), 1920–1926

MAY, 1920 (First Class)

1. Why is coal-dust from certain seams more easily exploded than that from others?

2. What are the disadvantages of using stone-dust and water together, for preventing coal-dust explosions?

4. What do you understand by the term "spontaneous combustion"? State what materials used at a colliery are liable to it, other than coal.

5. In the case of a rescue team working in an atmosphere obscured by smoke, how would members of the team communicate with each other and with the base?

NOVEMBER, 1920 (First Class)

2. How would you collect representative samples of dust from the floor, roof, and sides of an area of 50 yd. of road in the mine? Of the samples so taken, how would you prepare a portion for the incineration test? It is not necessary to describe the incineration test.

5. Make a sketch plan, and describe the general equipment of the room to be provided at every mine for rescue and aid purposes.

6. Describe the precautions you would take when about to work and whilst working coal or other mineral under quicksand, moss, or liquid matter (other than water).

OCTOBER, 1921 (First Class)

1. *Compulsory Question.* A sample of dust from an underground road gives the following analysis—

Moisture . . .	7·87 per cent
Volatile matter . .	20·30 ,, ,,
Fixed carbon . .	35·93 ,, ,,
Ash	35·90 ,, ,,

96 per cent of the dust passes through 200-mesh. Give your opinion on the relative importance of the constituents, and state your conclusions.

2. Many explosions have been caused by blown-out shots. Describe fully the precautions that a manager should enforce to prevent explosions occurring from this cause.

5. In the use of oxygen rescue apparatus, what are the causes of extreme distress or prostration of the wearer, and what are the precautions that should be taken?

MAY, 1922 (First Class)

1. *Compulsory Question.* A sample of coal-dust from an underground roadway, before treatment with stone-dust, gives the following analysis—

Moisture . . .	5 per cent
Volatile matter . .	25 „ „
Fired carbon . .	55 „ „
Ash	15 „ „

Assume that you now treat the roadway by distributing stone-dust in the proportion of one of stone-dust to one of coal-dust. Set out approximately the figures of a new analysis of the mixed dust. Consider the figures, and state in what respects and to what extent greater safety has been attained.

2. A colliery which worked a seam of coal by adits in the outcrop has been abandoned for some years, and the plant removed. Reopening is being considered and you are required to make a preliminary inspection. What dangers would you be prepared to meet with, and how would you proceed to carry out the inspection safely ?

4. A large fall of roof in the intake near the face has caused an accumulation of gas on the return side of a place in which two men are employed. The place can only be approached by passing through the gas by way of the return, with rescue apparatus. How would you proceed to rescue the men ?

NOVEMBER, 1922 (First Class)

1. *Compulsory Question.* A sample of dust has been collected from an underground roadway. Describe the tests to which it should be submitted and the constituents it is necessary to determine, stating which are safe and which are dangerous. Give approximate figures for (*a*) safe dust, (*b*) dangerous dust.

2. After an explosion, men are found unconscious from the effects of afterdamp at a considerable distance from the pit. Describe the first-aid treatment and care necessary upon finding them, and in removing them from the pit.

3. A serious explosion occurring during the working shift has extended to the bottom of both shafts, but without damaging the winding apparatus. How would you, as manager, organize and carry out the rescue of the survivors and the recovery of the workings ?

5. Set out briefly the special rules you would suggest to be observed by officials and workmen engaged in working a seam

of coal liable to spontaneous combustion, with the object of preventing its occurrence.

6. In the use of oxygen breathing apparatus, describe fully, and sketch, a complete circuit of the expired air and the changes it undergoes.

MAY, 1923 (First Class)

2. Assume that after an explosion the question of reversing the ventilation arises. Discuss the various matters you would require to consider before deciding whether such a step would be advisable or not.

4. Workings are approaching a large downthrow fault which it is presumed will bring down water-bearing red-sandstone measures opposite the coal seam. The exact position of the fault is uncertain. What precautions would you take, and how would you decide upon the boundary or limit of your workings ?

5. Discuss the conditions in coal mining that may detrimentally affect the health of the workmen, and the remedies or improvements that may be effected.

NOVEMBER, 1923 (First Class)

1. Write a short report on the present state of knowledge with regard to the dangers of coal-dust and the best means of combating them.

3. In the work of exploring and restoring underground workings after an extensive explosion, what are the principal dangers likely to be encountered, and how would you organize and carry out the work with safety and expedition.

5. In what main principles do the following rescue apparatus differ—

1. Oxygen apparatus.
2. Liquid air apparatus.
3. Smoke helmet.

Make a sketch of one type and state its limitations.

6. A longwall face 200 yd. in length is advancing in the direction of old workings likely to contain water, and there are grounds for suspecting the accuracy or completeness of the old plans. What safeguards would you adopt ? Accompany your answer by a sketch.

MAY, 1924 (First Class)

1. When taking samples of the dust from an underground roadway, how would you collect separately dust from the floor,

the roof and the sides respectively ? What principal differences would you expect to find, and why is it of importance that you should know the character of each sample rather than of the mixed dust ?

3. You are about to install apparatus for grinding stone-dust for use underground. What are the principal features of suitable machinery, and how would you decide on the quantity and quality of stone-dust to be produced ?

4. A thick seam of coal is being worked by the pillar and stall method, and trouble is experienced owing to the outbreak of fires in the pillars. What may be the cause of such fires ? What precautions should be taken to prevent them ? How may they be readily discovered and dealt with ? Accompany your answer by a sketch.

5. Accidents have occurred to members of rescue teams when engaged in actual work underground, either through some fault in the apparatus or some action or neglect on the part of the wearer. Set out the principal causes of such accidents and the precautions that should be taken.

MAY, 1925 (First Class)

4. Describe a central rescue station and its equipment, and the course of instruction for training teams of rescue men ; also the further training necessary to maintain efficiency.

5. In the event of a serious outbreak of fire at the screens near the shafts during working hours, what steps would you take to secure the safety and rescue of the men underground.

6. You have been appointed manager of a colliery in a coalfield with which you are not familiar, and you find that a seam of coal is being worked adjoining an old colliery which is full of water. It is necessary to make a careful scrutiny of the conditions and review the methods proposed. Give an account of all matters that would require investigation.

NOVEMBER, 1925 (First Class)

4. How may carbon monoxide be found in coal mines ? What are the characteristics of this gas ? How is it detected, and what precautions are necessary when its presence is suspected ?

5. A trained rescue team visits your colliery for the purpose of an underground practice. Set out a detailed programme of the work which should be included in such a practice.

MAY, 1922 (Second Class or Undermanagers')

2. What steps can be taken to prevent or reduce the production of coal-dust, (*a*) in the main roads, (*b*) in the subsidiary roads, (*c*) at the face ?

3. How do you account for spontaneous combustion being more common in some seams than in others, and how can the danger be reduced by methods of working ?

4. Upon the sudden occurrence of gob fire in a section of the workings of a mine, what steps would you, as undermanager, immediately take ?

6. How may underground fires be caused by electrical apparatus ? What precautions would you take to guard against them, and to be in a position to deal with them if they arise ?

NOVEMBER, 1922 (Second Class)

1. *Compulsory Question.* Describe in detail a method of collecting a sample of dust from the roadway of a mine for analysis, and say what are the important constituents that should be determined by the analysis.

2. Describe a coal-dust explosion experiment as carried out in the experimental gallery at Altofts or Eskmeals, and state generally the conclusions that have been drawn from such experiments. Make a sketch of the experimental gallery.

5. In cases of spontaneous combustion, what evidence may be obtained by analyses of samples of the air ?

6. In the use of rescue apparatus, what tests should the wearer make before and after putting it on ? And when using it in serious work, to what points should he regularly give attention to ensure his own comfort and safety ?

MAY, 1923 (Second Class or Undermanagers')

1. Discuss the merits and demerits of the following inert dusts : Flue-dust, shale-dust, sandstone-dust, limestone-dust.

2. How may the occurrence of carbon monoxide underground be accounted for ? What is its effect on the workmen and how may it be detected ?

3. How is spontaneous heating in underground workings detected in the earliest stage ? What are the evidences of progress, and why is progress rapid in one case and slow in another ?

6. Sketch suitable boring apparatus for use when approaching old workings containing water, and describe the complete operation of boring and afterwards closing one test-hole.

NOVEMBER, 1923 (Second Class or Undermanagers')

1. In using stone-dust underground, state (*a*) how you would distribute it, (*b*) where you would distribute it, (*c*) how you would decide on the quantity necessary and (*d*) how often you would repeat the distribution.

2. Enumerate as many as possible of the known or suspected causes of ignition which have resulted in colliery explosions.

6. Make a sketch of a type of rescue apparatus with which you are familiar and show by arrows the course of the circulation. Describe the means of purifying the respired air.

MAY, 1925 (Second Class or Undermanagers')

1. Why is it necessary to take samples of dust separately from the floor, roof, and sides of a roadway, and what differences would you expect to find in the samples ?

5. You are in charge of rescue men wearing apparatus underground. The work to be done is 200 yds. inbye of a fresh-air base, and is expected to occupy eight hours. How many men would you require and how would you organize the work ?

NOVEMBER, 1925 (Second Class or Undermanagers')

2. What are the principal dangers to be guarded against by an underground exploring party immediately after a colliery explosion, and to what matters should such a party direct their attention during the first day.

6. What have been the principal causes of flooding involving loss of life in mines ? Give instances, and state how such occurrences might have been avoided.

APPENDIX II

LIST OF ELEMENTS

Elements	Symbol	Atomic Weight
		O = 16
Aluminium	Al	27·1
Antimony	Sb	120·2
ARGON	A	39·88
Arsenic	As	74·96
Barium	Ba	137·37
Bismuth	Bi	208·0
Boron	B	11·0
Bromine	Br	79·92
Cadmium	Cd	112·40
Caesium	Cs	132·81
Calcium	Ca	40·07
CARBON	C	12·00
Cerium	Ce	140·25
Chlorine	Cl	35·46
Chromium	Cr	52·0
Cobalt	Co	58·97
Columbium	Cb	93·5
Copper	Cu	63·57
Dysprosium	Dy	162·5
Erbium	Er	167·7
Europium	Eu	152·0
Fluorine	F	19·0
Gadolinium	Gd	157·3
Gallium	Ga	69·9
Germanium	Ge	72·5
Glucinum	Gl	9·1
Gold	Au	197·2
Helium	He	3·99
Holmium	Ho	163·5
HYDROGEN	H	1·008
Indium	In	114·8
Iodine	I	126·92
Iridium	Ir	193·1
Iron	Fe	55·84
Krypton	Kr	82·92
Lanthanum	La	139·0
Lead	Pb	207·10
Lithium	Li	6·94
Lutecium	Lu	174·0
Magnesium	Mg	24·32
Manganese	Mn	54·93
Mercury	Hg	200·6

Elements	Symbol	Atomic Weight
		O = 16
Molybdenum	Mo	96·0
Neodymium	Nd	144·3
Neon	Ne	20·2
Nickel	Ni	58·68
Niton (radium emanation) . . .	Nt	222·4
NITROGEN	N	14·01
Osmium	Os	190·9
OXYGEN	O	16·00
Palladium	Pd	106·7
Phosphorus	P	31·04
Platinum	Pt	195·2
Potassium	K	39·10
Praseodymium	Pr	140·6
Radium	Ra	226·4
Rhodium	Rh	102·9
Rubidium	Rb	85·45
Ruthenium	Ru	101·7
Samarium	Sa	150·4
Scandium	Sc	44·1
Selenium	Se	79·2
Silicon	Si	28·3
Silver	Ag	107·88
Sodium	Na	23·00
Strontium	Sr	87·63
SULPHUR	S	32·07
Tantalum	Ta	181·5
Tellurium	Te	127·5
Terbium	Tb	159·2
Thallium	Tl	204·0
Thorium	Th	232·4
Thulium	Tm	168·5
Tin	Sn	119·0
Titanium	Ti	48·1
Tungsten	W	184·0
Uranium	U	238·5
Vanadium	V	51·0
Xenon	Xe	130·2
Ytterbium (Neoytterbium) . . .	Yb	172·0
Yttrium	Yt	89·0
Zinc	Zn	65·37
Zirconium	Zr	90·6

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